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ANALYSIS OF CUMULATIVE ERRORS ASSOCIATED WITH CATEGORY II AND III OPERATIONS WITH REQUIREMENTS FOR ADDITIONAL RESEARCH

by G. B. Litchford

Prepared by
LITCHFORD SYSTEMS
Northport, N. Y.

for

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SUMMARY

This report presents the results of a study and investigation of conventional and unconventional terminal flight paths for CTOL aircraft in connection with low visibility landing problems. The interrelationships of the geometry of possible approach paths, visual and electronic guidance equipments, and numerous aircraft piloting problems are reviewed. Pilot display requirements for optimizing these interrelationships under typical airline operating conditions are described as well as the flight path dispersions expected at the transition from instrument to visual flight guidance. Areas requiring improved simulation, flight validation, or other means of establishing statistically significant data for these critical operations are identified. The ILS standards will be examined to identify errors that affect the transition from instrument to visual flight.

I. INTRODUCTION

Category II and III operations face two basic problems. These problems, which are under serious investigation by NASA, other agencies, and the airlines, are: (1) noise abatement for the final approach paths, and (2) all-weather landing. Although each has its own specific problem areas, there are large areas of technical and operational overlap and similarity. For example, noise abatement flight techniques using steep approach paths (a glide path angle of about 6 degrees relative to the horizontal) terminate in one form or another in a conventional flight path before reaching the runway threshold area. From a conventional approach path of 3 degrees, a pilot of a jet aircraft normally flares the aircraft, transitioning from a straight descent path into a long curved path to touchdown. When transitioning from a steep approach path to the final segment, the pilot also enters into a long flare or "round-out" path, transitioning from, say, 6 degrees to 3 degrees. Thus, there is the common problem of flaring from one path into another: the steep segment of a noise abatement path terminates in a normal 3-degree final segment. The entire terminal flight path thus becomes a contiguous operation consisting of either two flare paths connected by a short straight segment or one path with a continuous flare.

Other common terminal flight path problems relate to the pilot's reliance on instruments for interpreting radio guidance commands. Normal visual guidance is inadequate in both cases. In tests and simulations of steep angle and low visibility flight, cockpit instrumentation designed for straight-line flight path trajectories in both the vertical and horizontal plane are employed. The inadequacy of such instrumentation for curved flight paths and the lack of a full understanding of the total interrelationships between the guidance path, the aircraft, and the pilot are becoming evident to investigators.

A. PILOT DISPLAYS

For example, tests have been conducted with steep angle paths consisting of two segments. Typically, the pilot flies the initial steep segment and then transitions to the second segment at a given rate (about 7 seconds per degree, or 21 seconds for a 3-degree path angle change). The pilot then momentarily stabilizes on the shallow (normal ILS) path before flaring to land. The instruments used do not display a curved track and the pilot is consequently "open-loop" between the two steady state conditions (of straight paths). Typically, the pilot retains the steep path too long, undershooting the programmed round-out when the standard flight director instruments are used. Analytical techniques are needed to determine the best method for guidance control and cockpit instrumentation for the aircraft following the long (about 5000 feet) curved path from the steep approach and the shorter curved path (about 3000 feet long) just prior to touchdown. Although under visual conditions the latter path is shorter, it may be longer for instrument conditions. Furthermore, with the introduction of the SST and the large jets (747 and C-5A), which will be more sluggish in power and aerodynamic response, both curved paths are apt to be increased in length.

B. PILOT CUEING

Pilot cueing using new visual and aural sensory inputs seems advisable. Even in pure visual cases, it is becoming more difficult for pilots of large or fast aircraft to judge vertical flight paths. This seems more difficult than judgment of the horizontal flight path. In the horizontal plane, the clearcut and obvious image of the runway centerline, and the perspective cues generated by displacement errors, make it very evident when a centerline correction is needed. Similar obvious and sensitive visual cues are not available in the vertical plane.

Furthermore, long aircraft create false illusions of height change while undergoing a pitch change during the flare.

C. FINAL SYSTEM CONSIDERATIONS

In noise abatement procedures that use steep glide angles, the IFR requirements must also be met. The aircraft will be higher for a given distance from threshold, and above normal IFR ceilings; thus the question arises as to what requirements will be needed for radio guidance in operational environments. Furthermore, the final phases (about 10 seconds for CAT II) will be visual, requiring that the tolerances of sink rate and the lateral and longitudinal positions relative to the specific landing point be clearly established within safe limits.

It is possible that if steepened IFR final approach paths are ultimately used, the final visual segment of flight will determine to a great extent what must transpire previously. Speed bleed-off and the reduction of sink rate are important, since some cases of sink rate as high as 2000 ft/min have been found possible. It is also not likely that two separate systems--one for low visibility landing and another for noise abatement (steep angle) guidance--will emerge. It is obvious that there is a requirement for one system that will achieve both results in such a manner that all aspects of the approach and flare-outs are contiguous and smooth. Consequently, understanding and solving the low visibility landing problem may well be an essential first step in solving the steep angle guidance problem.

One cannot assume that visual guidance will be available for the steep angle procedures, since the ranges to the runway threshold from critical noise abatement heights are far in excess of even the least demanding of the categorized landing conditions (CAT I--visual control from a 200-foot height associated with a runway visibility of 2600 feet). Although optical vertical guidance systems such as the ICAO, VASI, and Navy "Mirror" system have been considered for the steep angle approach, they would not be suitable for low visibility or IFR operation. Furthermore, it is likely that the desired aiming point of the steep path may vary considerably between aircraft. Optical paths are but single angle paths to a single ground point.

II. GEOMETRY OF PATH

A careful study of the path geometry is needed, because the steep angle approach for an aircraft with a given speed, configuration, mass, aerodynamics, etc., may need a different approach aiming point and steep path angle than another aircraft. Differing flare heights and differing threshold conditions are also likely in future operations where, in addition to conventional aircraft, SST, Jumbo, and V/STOL aircraft will be used. It is unlikely that a single path, or even a single contiguous, variable geometry path will satisfy all 1965-1975 aircraft flying steep angle approaches. Similarly, the flare properties just prior to landing already differ considerably between many existing aircraft--both civil and military. The flare path geometry below 100 feet of the B-58 has been measured to be quite different from a typical airline jet transport. It is likely that a flexible path with a variable geometry will ultimately be adopted. The SST, because of its size and possible increase in approach speeds, will differ in terminal flight path from a small twin-engine airline jet. Yet, both aircraft may want to employ noise abatement procedures or may want to conduct low visibility landings on the same runway.

Guidance techniques that are flexible enough to satisfy such divergent types of aircraft call for various guidance paths, differing considerably from the single path of existing ILS, particularly in the vertical plane.

For some years a microwave scanning beam system has been under test and development by FAA, USAF, and others. Langley Research Center employed portions of such a system for the early NASA steep angle flight research (C-47, T-33, and F-102). The basic characteristic of the remote scanning beam system is that of a full family of angles radiated vertically from as low as ½ degree to as high as 20 degrees. The addition of integrated precision range (now multiplexed in the FAA prototype equipment) permits the computation of flexible paths and variable geometry paths within the individual aircraft. A vertical, polar-coordinate system with about a ±50-foot range accuracy and about a 2/3-miliradian (0.003 degree) angular accuracy permits establishment of any path that is desired by use of a simple on-board computer. Thus, the coordinates can be made to serve all types of aircraft, requiring either steep angles or normal paths, with various dimensions being used for aiming points, flare heights, flare lengths, etc. Although this proven technique exists, better definitions are presently lacking of how it will integrate with the existing ILS whose glide path is a single angle, emanating from a single point. Current VHF ILS is too restrictive with its limitation forcing all jet operations to be constrained to a single path in the vertical plane.

III. ANALYSIS OF CAT II ILS AND STEEP ANGLE PATHS

A methodology for evaluating the current landing system (ICAO-ILS) is presented in this report. The individual errors have been described in several separate documents but never in a single document where an operational assessment could be made. Such an evaluation is pertinent to both the noise abatement flight paths and low visibility flight paths, because the problems of allowable dispersions of guidance errors are common to all paths. Since the ILS is so well known and widely utilized, it is essential to start with it for any analysis of instrumented approach and landing. Utilizing quantitatively derived data from this analysis (for both "live" flight testing and highly realistic simulation) will improve the methodology for examining the interrelated problems of guidance, piloting, aircraft performance, pilot performance, and new displays.

The error analysis is of direct significance to the aircraft low visibility landing studies now being conducted within NASA. All ILS errors and their impact on aircraft handling, safety, and aerodynamics of landing can be related to landing success. The allowable centerline errors, airborne equipment errors, and the normal flight errors due to wind shear, turbulence, aircraft response limits, etc., are of considerable interest. These errors may obscure the success of a normally good pilot/aircraft combination, since the corrective maneuvers upon visual transition from instrument flight may not be possible in the few seconds of flight remaining before ground contact occurs. Thus, though the use of ILS in low visibility will be discussed in great detail, the direct application of the analytical methods to the steep angle noise abatement paths are practical because:

1. Each steep path (both IFR and VFR) must terminate in a normal landing. Thus, the final part of a steep angle path must be the same as the final part of a normal landing path.

2. Much of the discussion on error distributions, the method of treating the errors in a "total" manner, and the allocated times and terminal conditions are nearly the same in transitioning from a steep path to a normal path. The individual quantities are different but the basic methods of analysis can be the same.

3. The use of separate methods for analytically treating the steep noise abatement paths and the normal low visibility paths will only lead to future confusion. Since they must eventually be a contiguous path, the treatment of the most sensitive situation seems appropriate (CAT II, low visibility) as the initial effort to establish the analytical methods.

4. A later treatment of the steeper paths that must integrate fully into the final landing paths can be done by anyone interested in the subject once the methodology is proven and acceptable.

When a pilot is flying without outside visual references and is dependent on the cockpit instrumentation, most flight track information displayed to him is simple in nature. It is simple because it is a steady-state condition for some period of time, so that he does not need to change mentally his references or perhaps the settings of his instruments. This is typified by the usual flight where a course is selected with certain cruise conditions of constant speed and height. These selected conditions are intercepted from other conditions and "bracketed" until the pilot (sometimes the auto-pilot) establishes a steady-state coupling to these conditions. Usually, only one set of conditions is changed at a time.

The ILS guidance is perhaps the most demanding of any form of flight in the way of precision flight and the minimum time available to achieve two-dimensional, precision flight paths in increasingly hazardous conditions (height reduction near the ground). Thus, the pilot normally brackets the localizer, intercepting and settling on it at a constant height. After establishing this, a steady condition exists in the lateral plane and the sloping vertical path is then intercepted and bracketed, establishing an appropriate rate of descent. Even though two intercepting and bracketing jobs have been completed, the steady-state descent and centerline path from around 1500 feet altitude to visual contact with the ground persists long enough for the pilot to stabilize within a given tolerance.

Upon visual contact with ground references, the pilot is no longer restricted to the type of flight he has been constrained to (achieving a series of steady state conditions, one at a time), but can now vary several parameters of flight simultaneously in a complex and non-restrictive manner. He may, upon breaking out from an ILS approach, change both his aiming points (vertical and lateral) simultaneously by starting a precision side-step maneuver and a duck-under maneuver correcting errors of the ILS guided flight. The flare path is then abruptly initiated near the ground. This is a continuously varying flight path in the vertical plane and lasts for as much as 15 seconds. Just a second or two from touchdown, crab angle must also be removed. Thus the tempo below a 100-foot height may be many times the tempo from 1000 feet to 100 feet.

It is obvious that the pilot can assimilate much more information with higher confidence level and subsequently achieve far more effective path control when he is under visual-flight conditions. However, in any marginal case where visual time is too short, the piloting techniques must be aided by non-visual anticipatory information before the beginning of visual flight path control.

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IV. LANDING SYSTEM ERRORS

Fundamental to all of our discussions in this report is the landing system that is now in widespread international use--VHF-ILS. The current landing system (ILS) consists of radio centerline guidance, vertical radio guidance, and optical systems (mostly lights) to align the pilot with the runway. The lower the visibility the more the dependence of the crew on radio guidance. The objective of radio guidance is to cause the aircraft to be aligned with the runway when first visual ground guidance cues become available. The lights preceding the runway threshold consist of a centerline string about 3000 feet long at all major airports and sometimes 1500 feet long at airports of lesser importance. The so-called CAT I landing criteria require a full set of lights and radio aids for landing. This (CAT I) condition requires that the pilot has achieved a visual contact with ground (at 200 feet of height above the touchdown reference level) sufficient to convince him that he can land the aircraft by only visual means.

The horizontal visibility along the runway near touchdown must also be ½ mile or 2600 feet. This is the so-called "200 and ½" condition of CAT I. The "100 and ¼" condition (CAT II) is similar with the limits cut in half. The visibility along the runway is measured in both cases by the projection of a light beam through the atmosphere to a photo cell receiver. The light intensity is calibrated for day and night and for the pilot's eye reaction. Its output is known as Runway Visual Range (RVR) since it measures a visual path about 15 feet above the runway surface. For Category II this RVR reading must be at least 1200 feet. For CAT III-A, no ceiling is stipulated but an RVR of 700 feet defines this condition as does an RVR of 150 feet for CAT III-B. The ultimate goal of true "blind" landing or zero-zero visibility is defined now as CAT III-C. This categorization, though helpful for regulatory and certification purposes, has led to a great deal of misunderstanding. Redundant electronics for reliability criteria of CAT III can be installed, though their operational use may not include the above visibilities. No statistical data exists from the field at the end of the 1966-1967 winter on the operational practicality of CAT II. Consequently, making CAT III-A systems and operations a mere extension of CAT II is highly speculative at this stage.

A. LANDING CRITERIA AND STANDARDS

The various national governments participate in the International Civil Aviation Organization (ICAO) to formulate standards for electronic and visual aids. The fact that a modern aircraft can land anywhere in the world today makes it imperative that the same standards for low visibility exist in the United States as in the United Kingdom, France, Germany, India, Japan, etc. Since several hundred landing systems are currently in operation in perhaps 30 to 40 countries, the same airborne equipment and pilot training must apply in each landing, no matter where or when it occurs. Standardization is highly significant to the safety and reliability of the operation as well as its value to the users.

Consequently, one of the best sources of such information is the International Civil Aviation Organization itself. ICAO is a branch of the United Nations organization. ICAO groupings are: the All Weather Operations Panel (AWOP), the Visual Aids Panel, the Aerodrome, Air Routes and Ground Aids (AGA) Division, the Air Navigation Commission, the Meteorology and Operations Division, and others. These ICAO groups publish voluminous reports. Typical are: Reports of meetings; procedures such as the (PAN/OPS) Procedures for Air Navigation Services--Aircraft Operations; Annexes to the convention such as Annex 10--Aeronautical Telecommunications (electrical standards); Annex 14--Aerodromes (location of landing and other aids), etc. Literally thousands of pages have been published in only the last five years by the many sources within ICAO and much of the current publications and interest is centered on all-weather operations, particularly low visibility landing.

The Fourth Air Navigation Conference Report describes the improvements thought necessary for ILS usage in CAT II, III-A, -B, and -C. The COM/OPS Divisional Meeting Report (meeting in November 1966) is about the latest thinking in many of these areas relating to the radio and visual guidance and their impact on piloting, various types of aircraft, runway lengths, etc.

Consequently, if one is interested in the total problem of landing a jet aircraft under low visibility conditions, one must study many of these recent documents to obtain an overall view. Interrelationships between optical and lighting guidance, ILS guidance, air traffic densities, piloting factors, and the aerodynamic capabilities of large jet aircraft do not exist in these documents. The integrated view or the "total" view of how these many technologies and human elements blend into a safe, dependable landing system is lacking. There is serious doubt that the current ILS accuracy criteria are satisfactory for CAT II if a high probability of landing is desired or is essential. This gross interrelationship can only be developed by analysis. A first attempt is presented here. Flight validation, and then extensive simulation using techniques with true realism of the situation can extract without risk much needed statistical data on several error components.

The high risk of even CAT I landing system operation and VFR landing of heavy jet aircraft is already evident. About half of all airline fatalities are directly related to landing. The reduction of fatalities in other areas is occurring, with a resultant increasing need to eradicate the landing accident. The increase of risk for CAT II as compared with CAT I (the only statistical base we have) is not known. The estimation by at least one expert is that the risk for CAT II will be two orders of magnitude greater than that for CAT I. This and other factors suggest that extensive research is needed to more realistically establish the risk levels of CAT II. The categorization of landing operations and equipments does not mean that all categories are not a contiguous representation of the same problem. The pilot and aircraft follow but one contiguous path, no matter how hard it is to define in writing or with visual and electronic aids.

The technical means of visibility measurement are such that to discriminate between CAT II and CAT III-A may be a matter of opinion rather than science, since we are dealing with such small differences and differences that vary rapidly with time, pilot psychology, visual acuity, and the viewing location relative to the runway. One must in reality, and as a scientific principle, consider the total problem and not break it into categories as it has been, even though it is necessary to categorize it in several steps for legal and administrative purposes.

The next major step (not yet achieved) of progressing from CAT I to CAT II calls for changes of 100 feet of decision height, and 1300 feet of runway visibility. These changes are sufficiently large that they can be approximately measured within reasonable limits. The change of only 500 feet of RVR between one operation considered safe or legal and another considered unsafe or illegal (CAT II to III-A) has not been scientifically documented. It is an administrative tool for progressive authorization of lower visibility based on experience with the preceding condition. The arrival at an unsafe condition should be determined beforehand by scientific methods; not by the statistics of airline landing accidents.

The current ILS and lighting standards are discussed briefly to find a means to flight validate or simulate these conditions quantitatively. For example, the limits of CAT I and II side-step maneuvers (correction of laterally dispersed errors) will vary drastically with aircraft size, speed, response, and pilot training (skill in picking up visual cues in low visibility). What are these limits in a quantitative form for CAT II, for CAT III-A, etc.? The methods employed to assess these limits will be to create maneuvering "windows" under these specified conditions. Whether the aircraft can maneuver from the error limits within the "window" to a safe, routine landing is the question at hand. Extensive testing and flight research will probably be needed to obtain answers for even one specific type of aircraft. There is an obvious difference between a large sluggish jet transport (stretched DC-8, 320-C, or 747) and a small, highly maneuverable light twin aircraft. The approach speed has a major influence; however, such limits as the maximum bank angle possible with underslung pods of most large jets drastically limits the extent of side-step possible when returning to centerline from a low decision height. The amount of increased vertical sink rate that can be safely arrested by pilot maneuvering also differs both for each aircraft and for each range of visual contact height in low visibility conditions.

B. STATISTICAL PRESENTATION OF LANDING SYSTEM ERRORS

In this section an attempt is made to relate the now clearly defined errors in the various elements of the ILS system to a probability of what total, centerline, vertical, and longitudinal error dispersion might be at the time of visual breakout. The pilot transition to visual flight guidance can create unexpected and vaguely evident serious errors. About 3 to 8 seconds are required to establish a wholly adequate visual reference. All parties seem to agree that this is the progressive way to proceed for the next two decades (instrument transition to visual landing). Consequently, what the pilot sees in the first few seconds after the first visual cues come above visual threshold, but before ground contact, is of enormous significance.

1. PROBABILITY PERCENTAGES

It is convenient in most navigational error discussions to quote the 95% probability of a given value not being exceeded. This, of course, means that when this value is established, some 5 percent of the readings will exceed this value. In statistical terms this closely approximates a 2 sigma, or 2 standard deviations, value which allows for more detailed statistical treatment if the actual measurements of the errors, preferably a few hundred, exist.

Each total system error is made up of several separately identifiable errors. For example, the VOR system total (or aggregate) error is composed of ground systems error, aircraft systems error, and piloting error. Since each of these is usually determined separately but can add in either direction with the others, the rule of the root-summed-square (RSS) method is employed to provide an overall system usage error. This is done by taking the square root of the sum of the squares (RSS); however, each element must be in the same statistical terms. For example, they should all be in terms of 2 sigma (or 95% probability); not in terms of one sigma and others in terms of three sigma. Since ICAO standards often express the individual errors in terms of varying probability, the errors must first be converted to a common probability basis before taking the RSS of the group.

This assumes, in most cases, a standard or normal distribution. If one side of the distribution is favored for some reason, special treatment is needed to take account of the lack of adherence to the normal or Gaussian distribution curve.

Table I on page 42 summarizes the current (1967) ICAO material on localizer errors. The information may be in the form of "95% probability" or "one standard deviation." In all cases they have been translated to "3 sigma" values. This relates all dimensions to a standardized error analysis that is consistent with the catastrophic nature of CAT II and III landing errors.

Generally speaking, fatalities in landing operations (including approach) outnumber all other forms of fatal accidents. The following table clarifies this point.

APPROXIMATE NUMBER OF SAMPLES PER THOUSAND EXCEEDING A GIVEN VALUE

Number of Standard Deviations of Sigma Values	Assume Gaussian	Assume Exponential
1	320.0	--
2	50.0	50.0
3	3.0	12.0
4	0.01	3.0
5	0.001	1.0

This is to say 320 times out of a thousand an allowable sigma ILS error is exceeded. At 4 sigma the exponential value is about 300 times as great as Gaussian values, and at 5 sigma it is nearly 1000 times. Inadequate data exists to determine whether ILS errors are Gaussian or exponential. Consequently, the term "worst error" is used. Also, no rules exist as to how many aborted approaches to CAT II limits will be acceptable. A recent UK study indicates that they have been as high as 40 to 45% for propeller-driven aircraft. With the risk assumed with a jet under these circumstances (estimated by some to be 10 to 100 times that of CAT I), the 3 sigma approach to CAT II and III ILS errors seems fully justified.

The skewness or asymmetry from a normal distribution requires special treatment. Inadequate data exist today on these measurements for suggesting anything but the simplest of treatment. However, at least the known exceptions do exist. In the case of the dispersion of vertical guidance, FAA measurements in 1962 indicated that the flight path deviation and curvature during visual flare-to-land did not follow a normal distribution, but had more dispersion on the high side than on the low side. This might be expected when the operation (flying toward a possible obstacle, e.g., the ground) is considered. The other case involves some of the more or less permanent radio beam-bends that can exist in a specific localizer or glide path that would not obviously follow a normal dispersion curve relative to the specific intended path and runway location.

Even though these are recognized phenomena that would result in other than a "normal" or "standard" distribution, others may be evident as research continues on this subject. For example, a cross wind causes the aircraft to head measurably into the wind (crab-angle) to maintain a course down the center of the localizer path. This also creates a lateral error in the main gear touchdown location, since most aircraft have the localizer antenna some distance longitudinally from the center of the wheel imprint. If, for example, a nose-mounted localizer antenna is 70 feet ahead of the aircraft's main gear and the aircraft is crabbing 6 degrees, the lateral displacement from the localizer antenna of the wheel touchdown will be about 7.5 feet. For a specific series of landings under a sustained cross-wind condition, this is not a normally distributed error. However, lacking anything more definitive and with the objective of avoiding complexities of statistical treatment, we will assume the RSS method of treatment. We will, however, insist that all errors be stated in the same probability terms. Since most of the ILS errors in ICAO standards are not so stated, they will be converted wherever necessary.

2. ONE, TWO, AND THREE STANDARD DEVIATION (S.D.)* ERRORS IN LOW VISIBILITY LANDINGS

For VOR and similar radio navigation systems it is popular to treat the errors in terms of 95% probability, or approximately 2 S.D. values. Thus, the three main errors (ground, air,

* A Standard Deviation (S.D.) error value is equivalent to a one sigma error value.

and flight) are treated and a total system error emerges. However, in VOR navigation, an error is seldom fatal to the pilot or aircraft. Either such errors go undetected or the airspace planning is based on separations between multiple aircraft, or aircraft and obstacles several times as great as the 95% figure. This in reality makes the system a 3, 4, or maybe 5 sigma system.

However, in landing of aircraft, the limits measured in linear units such as feet or meters become embarrassingly small for such treatment. Where no obvious bias along an airway exists, so that each side has many miles of airspace, such limited treatment is justified. The area below a glide path is highly dangerous, whereas the area above it is less dangerous. The latter case can lead to other difficulties, as we shall see, if used excessively. Similarly, the horizontal landing path (localizer) which is displayed to the pilot on his Course Deviation Indicator (CDI) differs radically from a VOR path indication since the only safe termination in CAT II and III is the relatively narrow width of the runway. This terminal condition is a very small fraction of the total width of the course indication.

In the case of the VOR, one can usually assume safety within the full scale limits of the CDI. It happens in many cases to be the same instrument that is used for localizer and VOR airway flying, but with different sensitivity. This VOR tolerance of flight following a CDI is far from adequate in the case of the ILS localizer indication as we shall see when we examine the errors in detail. With no radio guidance error (which never occurs), the typical runway is represented by less than one quarter full scale indication of the typical CDI. That is to say, other things being perfect, the pilot or autopilot must be controlling the aircraft within less than one fifth of the CDI indication in order to have the wheels of the aircraft pass safely over the inside edge of the runway. When the width of the wheels of a given aircraft is considered, crab angle, and errors of the radio guidance, this allowable piloting error turns out to be considerably less, approaching something as small as a 5% indication.

The point to be made here is that both 2 and 3 sigma values must be fully considered in view of the nature of the risk of the landing operation in CAT II. Where a 2 sigma error analysis sufficed in the past for normal air navigation of airways, 3 sigma or even 4 sigma errors must be considered in CAT III landings. This is not to say that the pilot will encounter a fatal situation, but merely to provide a means of quantitatively expressing the limits of aircraft position that can occur at the crucial transition from ILS or radio guidance to visual guidance. If the pilot, for example, has essentially an "on-course" indication yet upon visual breakout finds he is not aligned with the centerline of the runway, but considerably to one side, his confidence in maneuvering to the center in the short remaining time for a safe touchdown must be tempered with experience, training, and standards that fully inform him what is safe or not safe, since no time is available for careful decision making. This situation is a possibility, say, three times out of a thousand approaches.

Since this approximates the 3 sigma (99.7%) case, we will often discuss this three in a thousand probability of occurrence. Whether this is adequately high is not known. Beyond a 3 sigma value, errors need special statistical treatment. The question of the pilot aborting the approach in such cases (and many 2 sigma cases) must be raised. As in the concept of the pilot during takeoff being "go-minded," when a jet has reached certain ground heights, there may be a similar concept which says he must be "landing-minded" rather than "abort-minded," since the risks of both may be quite similar and high. London airport studies indicate that the number of missed approaches increases from 22% to 46% when the RVR falls from 2200 feet to

1300 feet. 46% is obviously intolerable, since the risk may have risen 10 to 20 times along with the rise in probability of a forced abort because of flight and guidance errors. It is of significance to note London's runways are much wider than most U.S. runways.

By examining these errors and their probability of occurrence, we can them simulate these conditions in actual aircraft or with electronic or other type synthetic flight simulation. What the pilot will do or can do under the circumstances can be measured quantitatively. This should aid in establishing a flight test program and a simulator program that utilizes such quantitatively derived samples rather than merely letting a pilot fly whatever is at hand and obtain a qualitative pilot opinion. The exposure to the various errors at specific, realistic visual transition points is important, since no reported controlled tests of this nature have been conducted. Real or simulated low visibility conditions have been examined in only a cursory manner. Most tests to date have been for a specific purpose, such as attempting to examine the sensitivity of the particular element that was the subject under investigation (lighting patterns--coloring of lights, intensity of lights, etc.). The full gamut of testing the spectrum of the probable errors has not yet been attempted.

Since examination of this in any great mathematical detail must await the collection of statistically significant samples by various methods of low visibility flight research, it is the intention here only to outline (1) methods for the collection of this data, (2) the extent of the 2 and 3 sigma errors in low visibility as now prescribed by the ICAO and FAA standards, and (3) the methodology of a more extensive program that will permit a scientific attack on this complex problem. The collection of this data must take place before the real significance of the 2, 3, or 4 sigma errors in a hazardous operation such as low visibility under CAT II and III-A and -B can be established. Such data must obviously be treated differently from normal navigational errors because of the high probability of a given error being fatal.

Some experts talk in reliability terms of one part per million or one part per 10 million. Often this is applied to only one aspect of the problem (say an automatic pilot failure). The use of even one part in a million for a total system criteria would be extremely stringent by today's standards. Yet, it must not be ignored conceptually in the research of low visibility landing problems. To approximate this, examples will be given of the sum of all errors and will be noted as the total "worst-case" error.

C. THE ICAO ILS-LOCALIZER STANDARDS

To reflect the latest thinking of error quantities now being considered, the ICAO COM/OPS Divisional Meeting of November 1966 (DOC 8636) issued in early 1967 is used as a reference. This reflects most of the All Weather Operations Panel (AWOP) reports and is nearly certain of international adoption. It details for example the revisions to the ILS specifications of Annex 10 that have been under review for several years.

The concept of a single "ILS Reference Point" has been abandoned, and 5 points now describe critical positions of ILS. These are illustrated in Figure 1. Point A is located on the glide path at 4 NM from threshold; point B is a similar point 3500 feet from threshold; point C is at a height of 100 feet; and point D is on the localizer 20 feet above the runway surface but 2000 feet inside the runway threshold. An "ILS Reference Datum-Point" directly above the runway threshold and on the center of the ILS path has also been added. The objective of the "datum-point" is to define the intersection of glide and localizer paths relative to threshold conditions. Variation in glide angle and location of the glide path transmitting

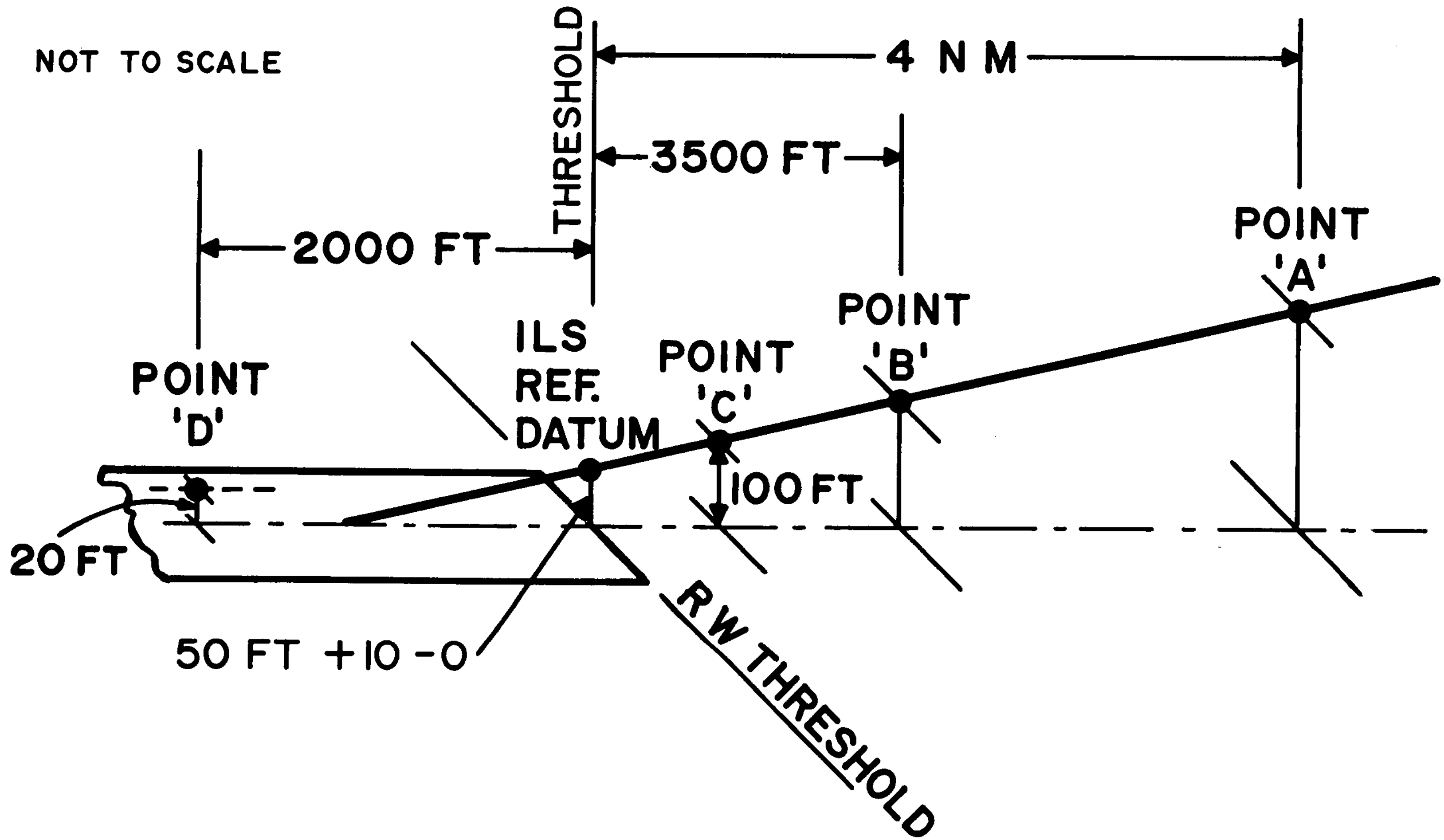


FIGURE 1

NEW ICAO/ILS REFERENCE POINTS

antenna do not cause wide variations in this concept of an ILS Reference Datum-point. For example, a low glide angle can achieve the same point (height above threshold) by being located further from threshold. Similarly, a high angle origin establishing the same point would be located nearer threshold.

The glide path is designed to establish the electrical center at a height over threshold of 50 feet plus 10 feet tolerance. Glide path variations result in large longitudinal variations affecting localizer guidance. The lower tolerance of threshold height of the glide path is essentially zero for CAT II and III. It can be 10 feet, however, for CAT I conditions. The negative tolerance has been removed for CAT II and III, inferring that the average height will exceed 50 feet and can be as great as 60 feet. The pilot's eye is near the electrical path but the wheels are typically 15 to 20 feet lower. This can be a highly sensitive dimension, since most data to date indicates that for current airline-operated jets the visual flight path over threshold is around 20 feet (wheel height) with 75% of all landings being less than 26 feet. This places the pilot's eyes about 40 feet above and over threshold. Whereas a CAT I glide path might be electrically only 40 feet above threshold, a CAT II or III glide path must be at least 50 feet above threshold and a path as high as 60 feet above threshold is permissible. This creates a spread of 20 feet in the specifications between CAT II and CAT I. The eye level dispersion is even greater; about 30 feet for variations in VFR, IFR, and aircraft. A 60-foot path would place the typical wheel height at about 45 feet, whereas a 40-foot path would place the wheel height at 25 feet. In both cases the assumption is that the sink rate and flight path are established by flying the 2.5 to 3.0 degree path of the ILS glide slope. The 1962 FAA visual landing measurements data indicated that the normal visual path is about half this angle (also about half the sink rate) and displaced below the lowest of the specified ICAO paths. This situation also has a large bearing on the "approach-aiming" point, which is the point the pilot would fly toward on a straight glide path and touchdown if no flare path was executed. This is visually quite evident to the pilot upon landing, and there is a growing indication that pilots "duck-under" to correct the ILS aiming point to more nearly meet their visually desired flight aiming point. There is pressure from those using radio altimeters to establish as much height over threshold as possible, since the requirement exists for a level, plane surface for the radio altimeter controlled flare to function satisfactorily. Terrain irregularities before threshold exist at most airports in the United States. The construction standards call for only 200 feet of flat overrun. Many airports have terrain variations totaling 30 to 100 feet; less than 3500 feet from threshold.

1. ICAO ILS POINTS A, B, C, D

Points A, B, C, D are utilized in the standards to define the course quality, beam bends, pilot errors, etc., at the specific distances from threshold or touchdown. The points have different allowable errors for CAT I, CAT II, and CAT III. Consequently, one can obtain rather definitive data from the standards that have been established for these operations. The relationship of these specific errors to aircraft maneuvering limits and pilot handling problems can then be examined on a 1, 2, and 3 sigma basis, since the probability limits are given in most cases. Figure 2 illustrates the localizer course widths at threshold and at point B. This is the maximum allowable width and is defined in the cockpit by full scale deviation of the localizer needle consisting of a signal of 150 microamperes through the CDI. This is also defined in terms of modulation percentages and is known as the Difference in Depth of Modulation (0.155 DDM) between the 90 and 150 cps, right-left, signals.

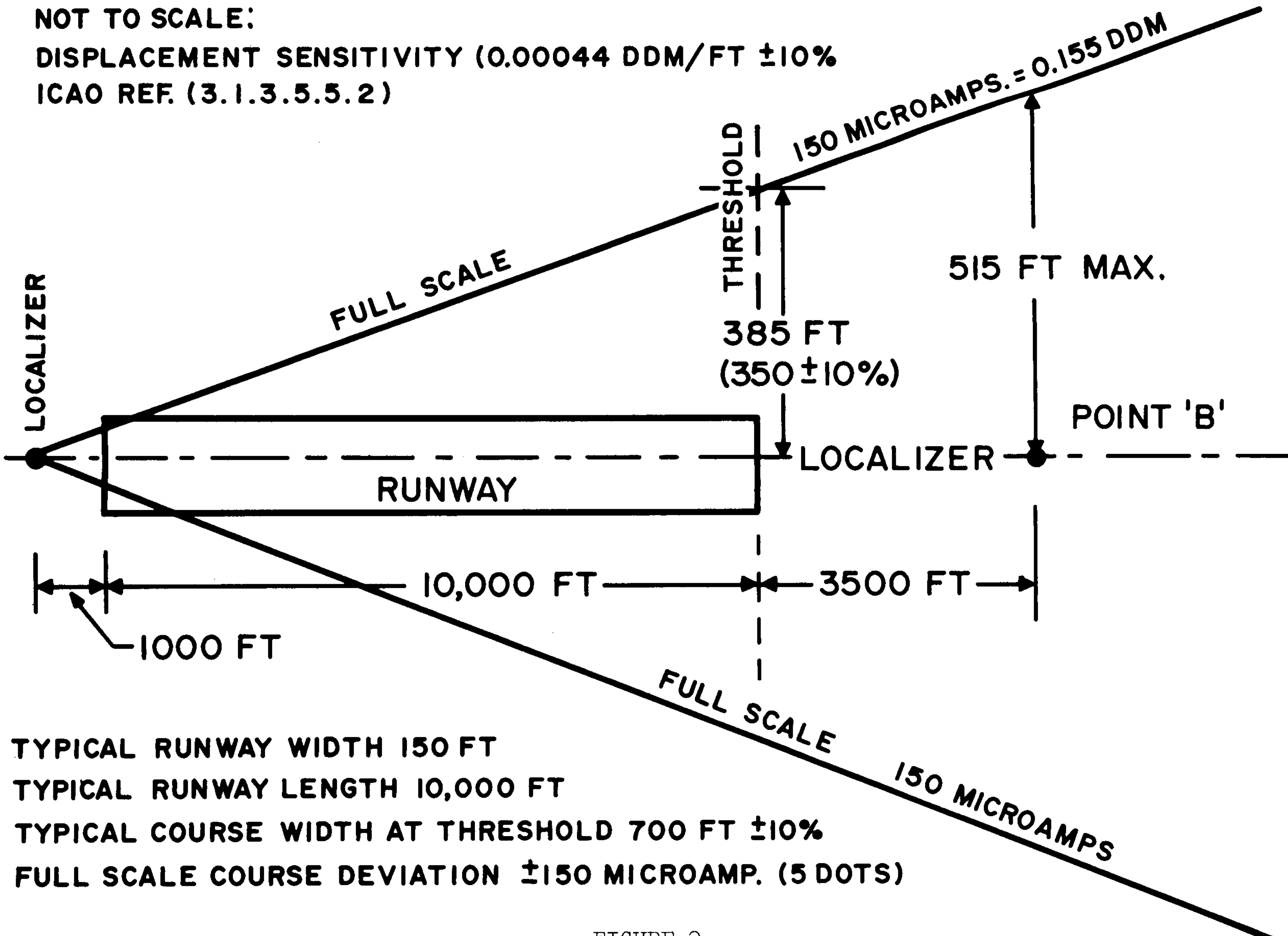


FIGURE 2

ICAO/ILS LOCALIZER COURSE WIDTH
AT THRESHOLD AND AT POINT B

The localizer sensitivity is varied in angular units to achieve the nominal 700-foot course width (±350 feet) at the threshold. Angular sensitivities of between 2 degrees and 3 degrees for a half sector width are used to achieve this result. The narrow angle being used on long runways and the wide angle on short runways is illustrated in Figure 3. Figure 4 illustrates the pilot's display sensitivity in terms of deviation from runway centerline. At point B the aircraft is 3500 feet from the threshold but 14,500 feet from the localizer transmitter in this example. An example of a shorter runway with a wider angular course results in slightly wider dimensions (about 10% more) at this point. However, as the aircraft approaches the threshold the errors in terms of feet for a given CDI current or other error indication is the same for short and long runways as shown in Figure 3. Following the 3 sigma concept, the widest course will be used in these examples, since there is a tolerance of ten percent on the course width. This results in the pilot having (point B) a full-scale indication (other errors being zero) when he is about 500 feet off the extended runway centerline. Point B is at an approximate height of 200 to 250 feet depending upon glide angle and path height at threshold.

Figure 5 illustrates the errors according to the recent ICAO standards. It will be noted that when these are related to point B, each has a different sigma value as established by ICAO. For example, receiver centering is given in one-sigma values and course bends are given in 2 sigma values. The total worst case is shown for illustrative purposes by adding all tolerances as stated without converting to a common base, including the 25-microampere piloting error quoted in FAAAC 120-20 As noted in Figure 4, this is equivalent to about 25/150 or 1/6 of a full-scale deflection. On CDI indicators with a "5-dot" full scale, this is an amount less than a "1-dot" flying

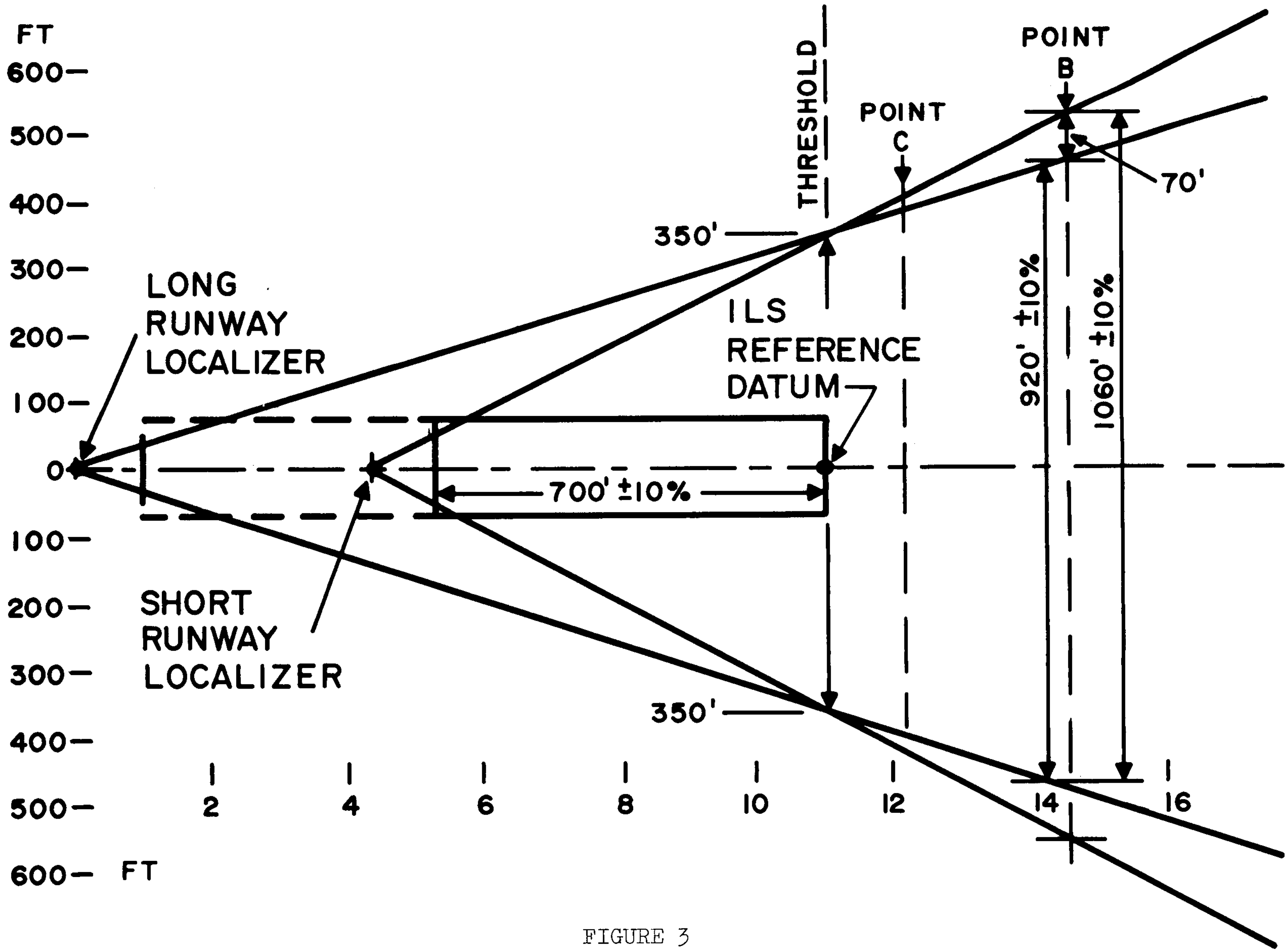


FIGURE 3

VARIATION IN LOCALIZER COURSE WIDTHS AT POINTS B AND C

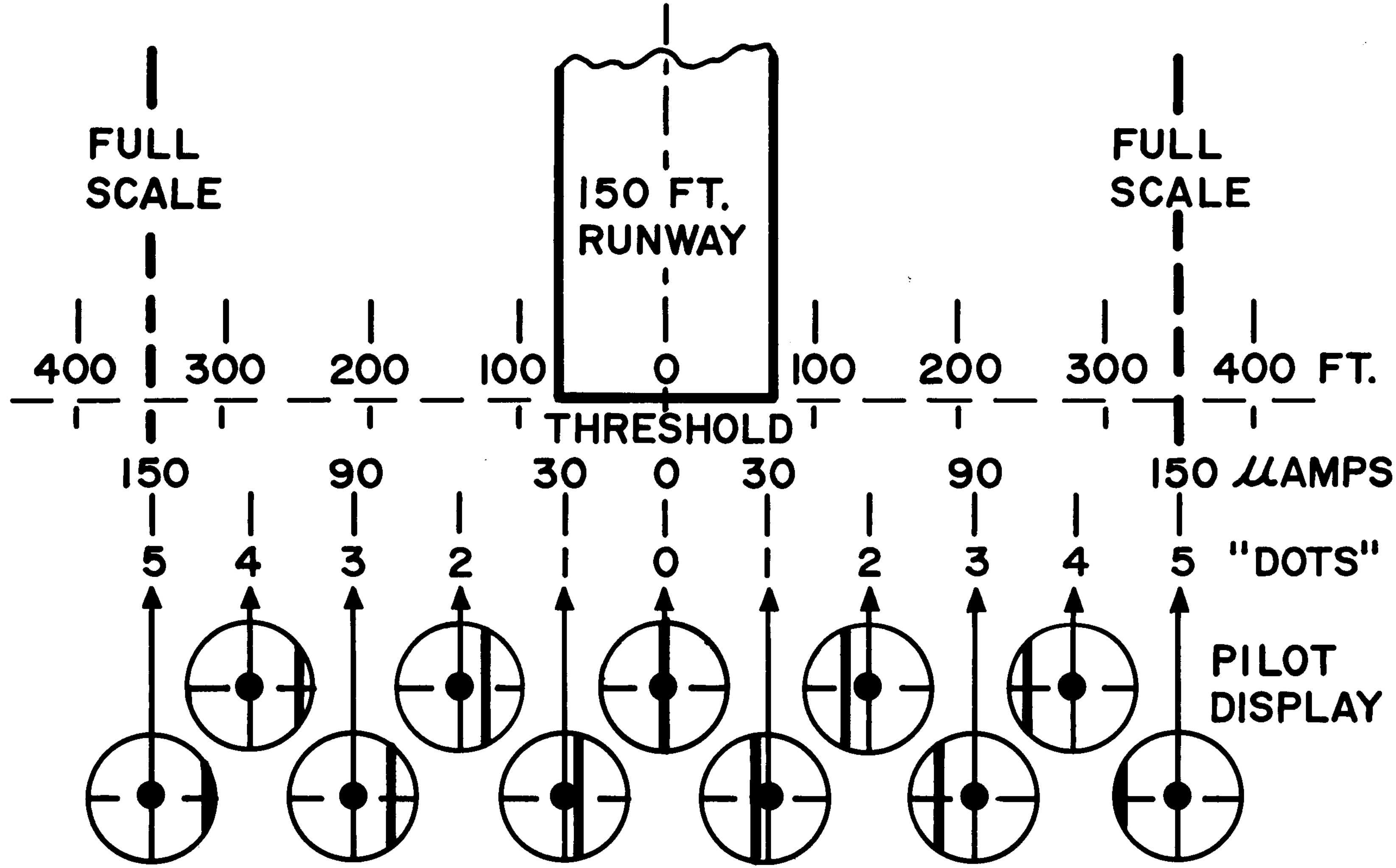
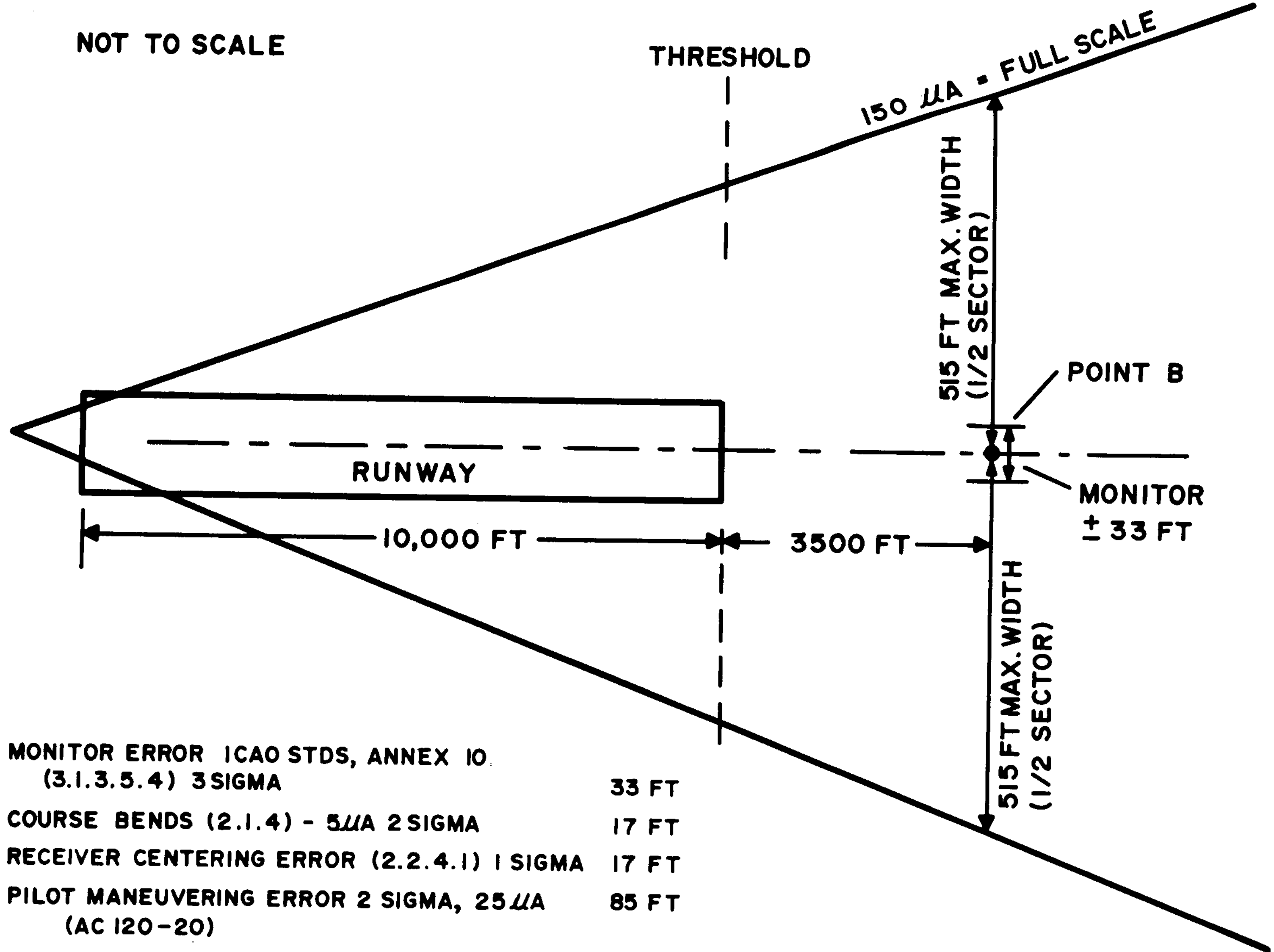


FIGURE 4

ICAO STANDARDS FOR LOCALIZER THRESHOLD SENSITIVITY



MONITOR ERROR ICAO STDS, ANNEX 10 (3.1.3.5.4) 3 SIGMA	33 FT
COURSE BENDS (2.1.4) - 5 μA 2 SIGMA	17 FT
RECEIVER CENTERING ERROR (2.2.4.1) 1 SIGMA	17 FT
PILOT MANEUVERING ERROR 2 SIGMA, 25 μA (AC 120-20)	85 FT
TOTAL (WORST CASE)	152 FT

FIGURE 5

ICAO/ILS LOCALIZER COURSE ERRORS AT POINT B accuracy. It is interesting to note that the CDI indication error allowed for the VOR piloting error is 1/4 scale, equivalent to 2.5 degrees, in the VOR system calculations. No reasons for this difference are indicated, probably because no valid test data exists.

Let us assume the following error distribution:

Monitor errors 99%--thus 1% fall outside this value.

Course bends 95%--thus 5% fall outside this value.

Receiver centering errors 68%--thus 32% fall outside this value.

Pilot maneuvering errors 95%--thus 5% fall outside this value.

It can be seen that it is difficult to arrive at an assessment of the errors in representative cases. Consequently, Figure 6 makes some assumptions that need validation. By converting the errors to values with common probability figures, they can be given an RSS value. As indicated previously, because of the high risk at these and lower points on the ILS that occur without visual contact, 3 sigma values are considered conservatively realistic in analysis of CAT II situations.

When several errors are treated, the square root of the sum of the squares (RSS) is the method usually employed to represent the most probable error (assuming each error is in equivalent terms). The total of 3 sigma values for each element of this group is 236 feet, the RSS of these errors is 143 feet. It is interesting to note that piloting or flight error alone contributes 127 feet of error, so that with this treatment of error data all other guidance errors have an apparent small contribution.

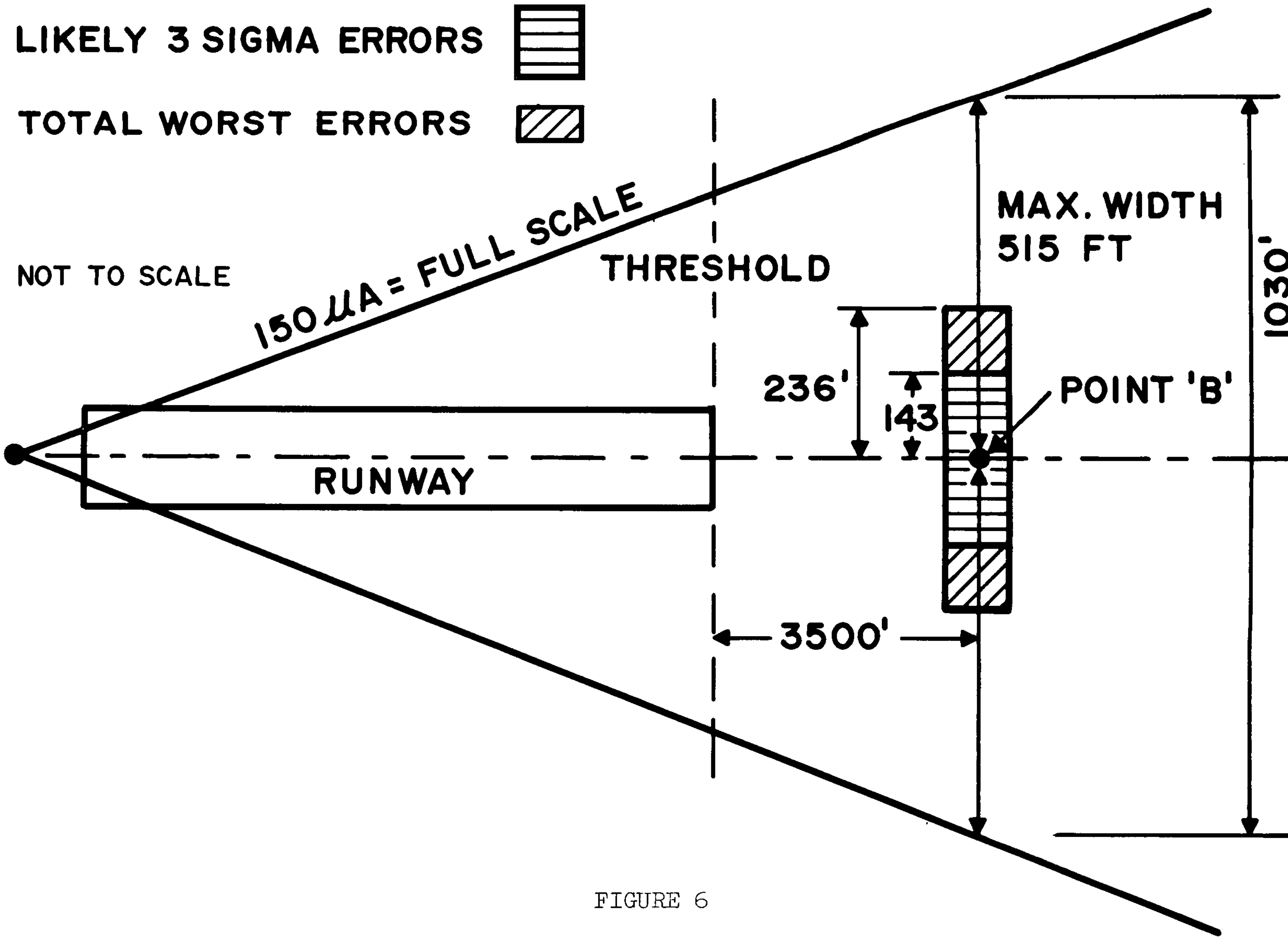


FIGURE 6

CONVERSIONS OF ILS LOCALIZER ERRORS
TO COMMON (3 SIGMA) ERRORS

CONVERSIONS OF ILS LOCALIZER ERRORS
TO COMMON (3 SIGMA) VALUES

	Point B
Monitor Error.	33 ft.
Course Bends	25 ft.
Receiver Centering Error	51 ft.
Piloting Maneuver Error.	127 ft.
Flight Error (Manual-Auto)	
Total Worst Errors	236 ft.
Sq. Rt. of Sum of Squares.	143 ft.
Total Navig. System Errors	109 ft.
Sq. Rt. of Sum of Squares (Navig. Error)	66 ft.

However, the errors of the navigation equipment taken alone can amount to 109 feet in the worst-case and to 66 feet RSS by this method. The logic of this simple statistical treatment is that all errors follow normal dispersions and will not add in the same direction. If normally distributed, the total effect will tend to be represented by the RSS figure.

However, as noted previously, this needs much deeper treatment, as it is possible for a more or less permanent course error to prevail at point B in a localizer or a piece of radio equipment so that it cannot be considered a truly normal error. Similarly, a wind shear can blow an aircraft off course at lower heights, causing additional flight errors to develop which may not have been previously encountered. The pilot has no reliable way of detecting course deviation from wind shear until he is observing the flight path of the aircraft along with the attitude of the aircraft by visual reference to recognize ground objects. Although admittedly rare, the total error possible is shown as 236 feet at point B. This admittedly has a likelihood of perhaps $1/10^8$ if a truly normal distribution of errors exist. If not, it can have a probability of occurring of, say, $1/10^6$. We have not considered at this point two additional localizer errors that can be significant: crab angle and beam deformation by objects moving on the airport. Crab angle is far more sensitive near threshold that at point B; it will, therefore, be discussed later in conjunction with other threshold criteria.

2. MONITORING ERRORS

Although ICAO calls for a ±25 foot monitoring tolerance of the localizer signal at threshold, they recommend that this be held to ±15 feet, if possible. When the square root of the sum of the squares is taken, this has little effect as noted in comparing case I and case II below.

	Case I	Case II
Monitor	25 feet	15 feet
Course bends	20 "	20 "
Receiver centering	39 "	39 "
Pilot (flight) error	97 "	97 "

(Case I) $\sqrt{625 + 400 + 1521 + 9409}$ or $\sqrt{11955} = 109.5$ feet

(Case II) $\sqrt{225 + 400 + 1521 + 9409}$ or $\sqrt{11555} = 107.5$ feet

As seen, the difference in the monitoring error adds less than 2% to the RSS (3 sigma) error. The large effect of the flight error on the total dispersion of the aircraft laterally from centerline requires considerable evaluation. Given as 25 microamperes for a 95% (2 sigma case) it represents 37 microamperes at 3 sigma and 37/150 or about 25% of full-scale deflection (1.25 dots of a 5-dot CDI--see Figure 4). Only simulation and flight validation can provide a statistical base for assessing the reasonableness of the value of the flight error. Wind shear, piloting techniques, aircraft response, aircraft size, speed, etc., will probably produce a different value for flight error of each aircraft. It is not known how realistic the 95%--25 microampere value is (FAA AC 120-20); it may be too small in some cases and too large in others. Certainly, it will have considerable significance for the SST.

Since point B is close to a CAT I ceiling, it is interesting to note that the pilot has some 5000 feet of forward flight to correct for this lateral off-set error. Measured (average) touchdowns occur about 1500 feet from threshold. This is ample time to conduct a side-step maneuver of about 140 feet, since with a height of 200 to 250 feet and an associated visual range of 2600 feet, some reasonable bank angles can be employed. Much larger bank angles are safe at point B than at lower heights. At a 200 feet/second forward approach speed, some 25 seconds elapse from this point to touchdown.

This allows about 1.8 seconds for each 10 feet of lateral correction. With further limited bank angles, this figure can rise to about 4 seconds for each 10 feet of lateral correction.

3. POINT C--100 FEET

Figure 7 is a similar illustration made at point C, which is a point 100 feet high on the indicated glide slope.

Assuming a typical glide slope and threshold (path) height, this point is located about 900 feet from the threshold. It may vary from about 750 feet to about 1150 feet in distance from threshold depending upon the combination of path angles (from 2.5 to 3.0 degrees) and path height over threshold (from 50 to 60 feet). We will discuss vertical guidance errors in a later section, but some brief note that the total longitudinal dispersion of errors can be from 500 to 1700 feet is needed here since the ICAO definitions for the 100-foot visual "decision-height" determine the spread of distances that the aircraft can be from the threshold.

Figure 8 shows the threshold conditions of a 3 sigma (3/1000) system error and the "worst-case" errors. Even the 2 sigma system error is of concern since it amounts to about 150 feet ($\pm$75 feet) or the total width of the typical (instrument) runway. Table I summarizes these errors.

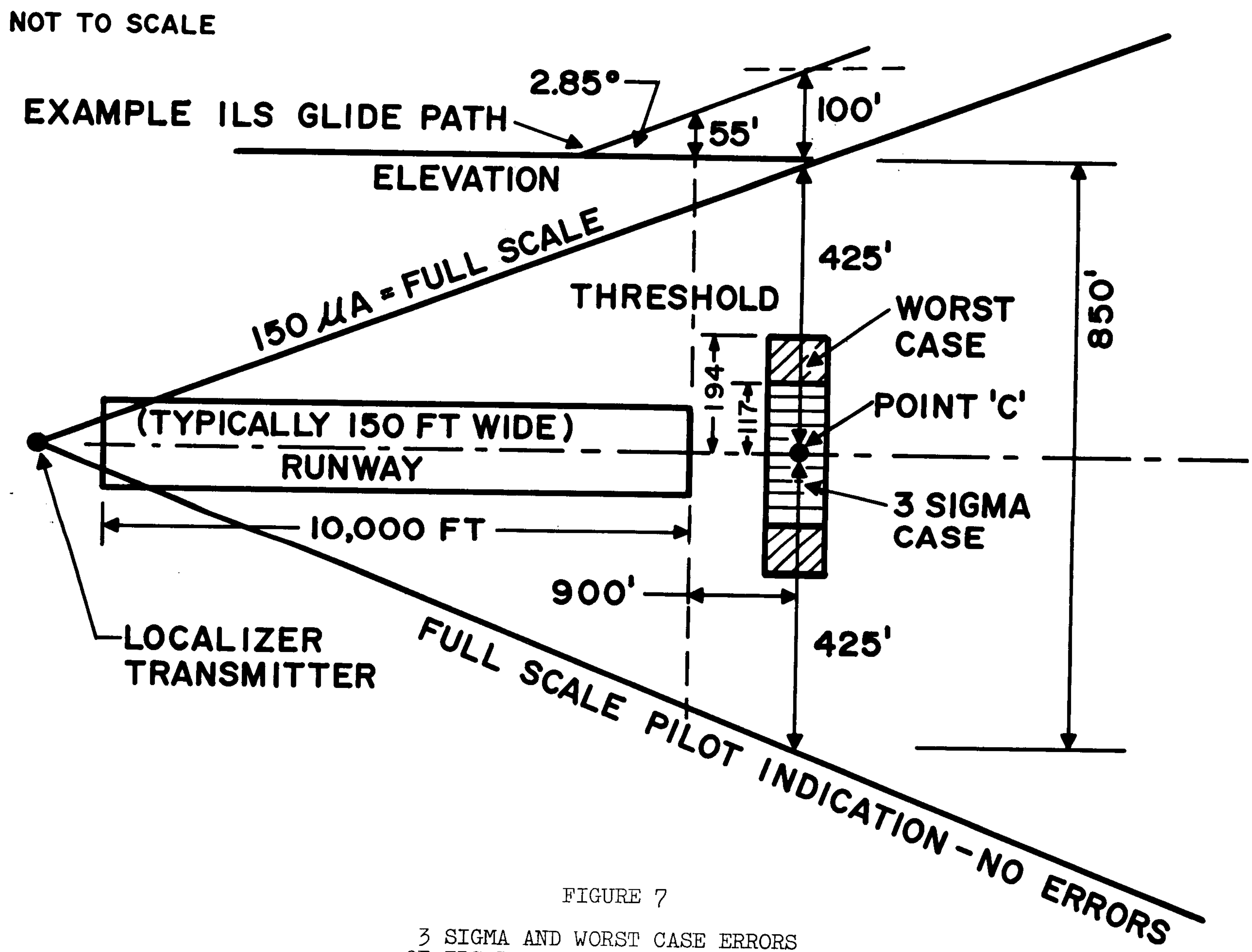
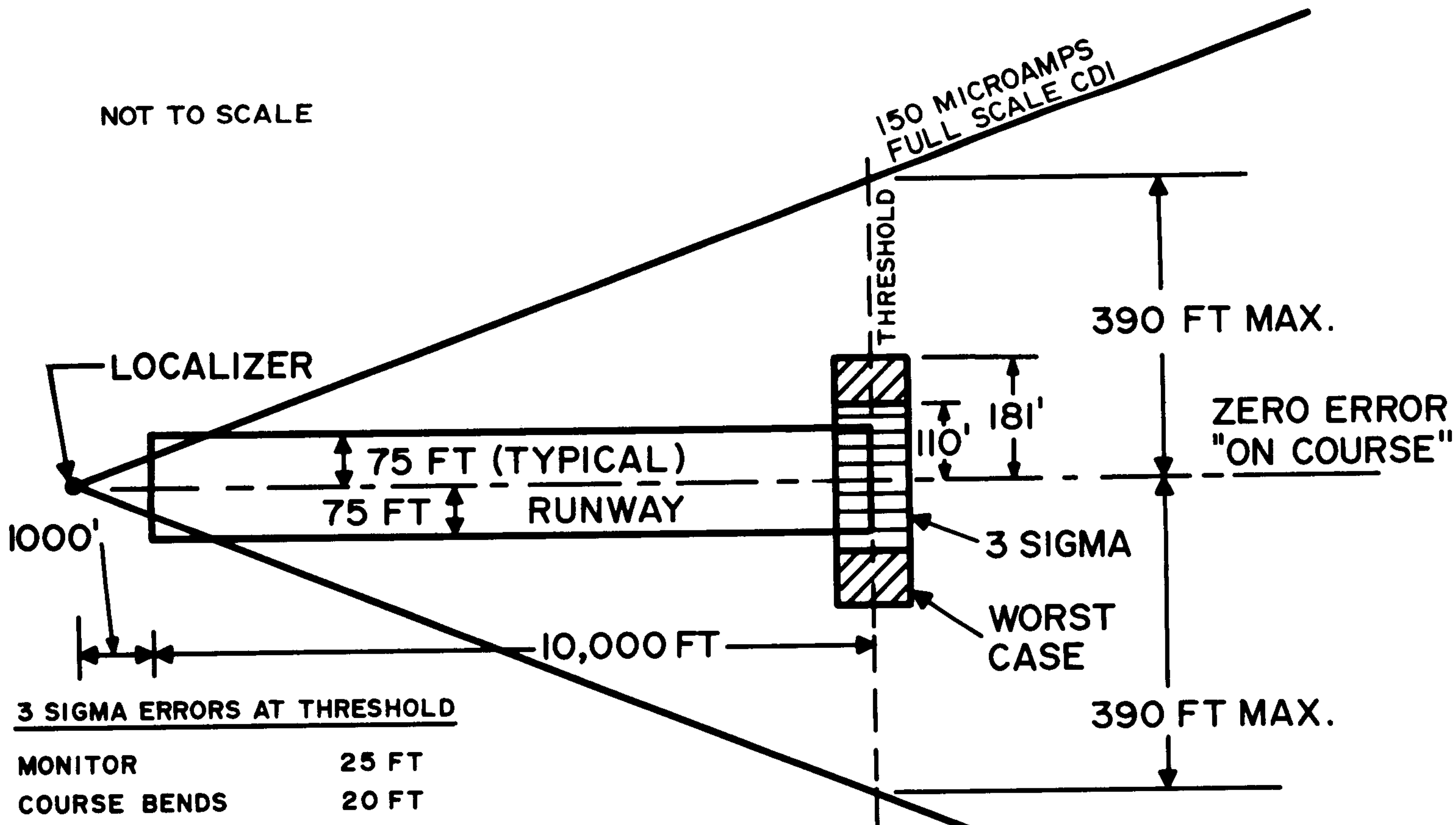


FIGURE 7

3 SIGMA AND WORST CASE ERRORS
OF ILS LOCALIZER AT ICAO POINT C

NOT TO SCALE



3 SIGMA ERRORS AT THRESHOLD

MONITOR	25 FT
COURSE BENDS	20 FT
RECEIVER CENTERING	39 FT
PILOTING ERROR	97 FT
TOTAL WORST CASE	±181 FT
SQ. RT. OF SUM OF SQS	110 FT
NAVIGATION TOTAL	84 FT
SQ. RT. OF SUM OF SQS	50 FT

FIGURE 8

3 SIGMA ERRORS AT THRESHOLD

CONVERSIONS OF ILS LOCALIZER ERRORS
TO COMMON (3 SIGMA) VALUES

	Point C
Monitor Error.	27 ft.
Course Bends	21 ft.
Receiver Centering Error	42 ft.
Piloting Maneuver Error.	
Flight Error (Manual-Auto)	104 ft.
Total Worst Errors	194 ft.
Sq. Rt. of Sum of Squares.	117 ft.
Total Navig. System Errors	90 ft.
Sq. Rt. of Sum of Squares (Navig. Error)	55 ft.

TABLE I

LOCALIZER ERRORS

Nature of the Error	ICAO Reference	ICAO CAT II Amount	3 Sigma Value at Threshold	3 Sigma Value at Point C	3 Sigma Value at Point B
1. Centerline Monitor	3.1.4.5.4	±25 ft. (threshold) ±15 ft. (recommended)	25 ft	28 ft	33 ft
2. Course Bends	2.1.4	±5 microamperes or .005 DDM* (2 sigma)	20 ft	22 ft	26 ft
3. Receiver Centering (airborne)	2.2.4.1	±5 microamperes (1 sigma)	39 ft	43 ft	52 ft
4. Polarization	3.1.3.2.2.1	0.008 DDM for 20-degree bank angle	Unknown for specific aircraft		
5. Linearity	3.1.3.5.5.3	±10%	Applied to above as 3 sigma		
6. Sector Width	3.1.1	0.00044 DDM/ft			
Sector Width	3.1.1	700 ft at Threshold			
7. +10% Tolerance		770 ft at Threshold	770 ft	850 ft	1030 ft
Half Sector Width		Above	390 ft	425 ft	515 ft
Pilot CDI Display Full-Scale Deflection	3.1.1	±150 microamperes = 0.155 DDM = ±350 ft at Threshold	Various errors depending upon number of centered galvanometer movements of DC/AC conversion for flight director or autopilot coupling		
8. All Flight Errors (crab-angle, wind-shear, normal track following engine-out, poor heading)	FAA/AC 120-20	FAA ±25 microamperes or 1/6 full scale (less than "one dot" 2 sigma value)	97 ft	104 ft	127 ft

* DDM = Difference in Depth of Modulation

D. USEFUL RUNWAY WIDTH

Not all of the runway width is available to a pilot landing a large jet transport. The localizer antenna for defining runway centerline is normally in the nose and on the central axis of the aircraft. For most aircraft, from 12 to 15 feet must be allowed to the outboard main wheel from the aircraft longitudinal centerline. Crab-angle increases this figure. The two dimensions reduce a 150-foot runway to an effective width of about 90 feet, since the pilot has about this much lateral freedom. Figures 9, 10, and 11 illustrate these important points. Thus, the 3 sigma case places the aircraft 110 feet off centerline and the 2 sigma case 73 feet off centerline. The maximum allowable is 45 feet off centerline; thus, neither case would be adequate. Another way to state this is that only the 1 sigma case would come close to matching the dimensions of the useful runway width. This is to say that only about 68% of the cases would be within the tolerances. This would suggest that about one approach in three (32%) would have to be aborted for this reason alone. Since adequate visual contact cannot be made in CAT III until over the runway, these tolerances would result in excessive aborts. Even in CAT II, cockpit cutoff eliminates all but about 2 seconds visibility of approach lights after passing 100 feet.

These are important aspects of the problem that should be quantitatively simulated and flight validated in detail. More will be said on how to utilize the data for these purposes later. In such low visibility it is likely that the pilot will not find that a "look-see" descent to minimums and then an intentional pull up will be acceptable to him or the authorities. The visual cues are too fragmentary and the fact that what might be displayed as "on" runway centerline will not occur when the pilot sees the actual runway; this can be a serious problem. Even the navigational system errors can have an RSS value of 50 feet, still outside the useful runway width. This implies that the pilot can have his indicator centered (within one microampere) and still be 50 feet off centerline for a 3 sigma case and 37 feet off center for a 2 sigma case.

1. LATERAL MANEUVERING LIMITS

It can be argued that the pilot, noting his displacement on the CDI, will be alert to the fact that he should expect to see the runway in a certain direction and with a certain perspective. Wind shear and crab angle defeat this assumption. The errors of the guidance system, unknown to him, can still be such as to severely misalign him. Even though he has flown before becoming "visual" to a centered condition on the CDI, this can occur. This raises, of course, the question of what is realistic for pilot performance on the CDI. The FAA AC 120-20 criteria of 25 microamperes for either manual (flight director) or automatic flight control, infers that less than 1/6 scale or a deflection of less than 17% of full scale is expected of the pilot. As indicated in Figure 7, this amounts to 104 feet at point C for a probability of 3 sigma (3/1000). For a 2 sigma probability (50/1000) this figure is about 70 feet. This implies that when the pilot sees the threshold of the runway he can be nearly aligned with one edge.

This example assumes that the guidance signal has no error in either direction. The real question (only answerable by flight validation and extreme, realistic simulation) is: "CAN THE PILOT LAND FROM THIS POSITION?" The dynamics of the aircraft, the bank limits at these low heights, and other factors will determine this. Since the pilot is but 900 feet from threshold (in the best case), he certainly cannot be over centerline before crossing the threshold. His displacement from the runway edge will depend upon the aforementioned factors.

The length of the flight path needed to do a lateral side-step maneuver (under cross winds) that may terminate only a few feet above the ground has measurable quantities for each aircraft. The measured quantities will then determine at what point the pilot would be sufficiently near centerline to touchdown. If, for example, the side-step of over 100 feet laterally from a height of 100 feet starting 900 feet from threshold required 6000 feet of forward flight because of bank angle limits (somewhere between 2 to 5 degrees), the aircraft obviously would not land. This is a lateral rate of as much as 30 feet per 10 seconds. A rate of 20 feet per 10 seconds is sometimes considered a maximum for small errors while longer periods per 20 feet are required for larger errors. Much of the ICAO and FAA data is derived from an RTCA (Radio Technical Commission for Aeronautics) report (entitled "Standard Performance Criteria for Autopilot/ Coupler Equipments," SC-79 paper #31-63/DO-118.) This document describes the trade-offs between bank angle limits, rate of roll limits, and the ability to reject beam noise by essentially using the aircraft dynamics as a narrow-band filter. Encountering wind shear, severe cross wind, or a large lateral side-step maneuver, the sluggish response so developed is such as to require a lengthy flight track for correction to centerline. If, on the other hand, bank limits were increased to 30 degrees and the aircraft was made much more responsive to the beam signals, many beam noises would enter the control system sometimes causing violent roll maneuvers and heading changes.

Replacing the autopilot with the human pilot does not change the picture appreciably. He will also limit roll angle and rate at the lower heights and be reluctant to make any sizable changes below 100 feet in the course direction or lateral track of the aircraft. The larger the aircraft the more this will be true. Extreme care should be exercised in assuming that the Boeing 747, the SST, and the C-5A will behave as well in low visibility as the already marginal characteristics of the current four-engine jet transports. Questions of whether to use two or three sigma limits for CAT II and the response of aircraft to lateral side-step maneuvers below 100 feet are amenable to quantitative assessment even for these aircraft.

Thus, Figure 7 raises several pertinent questions concerning the allowable safe maneuvering to correct side-step errors below a height of 100 feet. The limits can be developed independently for specific cases by assuming a given aircraft, physical dimensions, approach speed, wheel tread, roll rate, and angle limits. A side-step maneuver contour can then be generated that is considered to be suitable for the allowable cross wind, engine-out, and wind shear conditions landing on a typical 150-foot wide runway. This maneuver line would also include delays for pilot recognition, control action, and aircraft response. An assumed bracketing error is needed since the change in height could cause the aircraft to encounter a wind change requiring the establishment of the best heading by displacement error-rate to sustain the aircraft within runway centerline limits. If this is computed and validated for various typical IFR approach speeds (measured to be higher in IFR than VFR), each aircraft would then have maneuver contour limits establishing the amount of deviation from centerline that is allowable at the 100-foot height.

It is believed again that 3 sigma values should be used (3/1000), since the pilot can obviously abandon the approach sooner than executing a lateral correction that may require 10 seconds for every 20 feet of lateral error. From this methodology the number of expected missed approaches can be determined. It may be that the 25-microampere error can be reduced by better pilot training of CDI flight-following. Possibly a given 25-microampere indication might represent only 50 feet of lateral deviation rather than 100 feet. This raises the question of tightening the entire approach and threshold sensitivity criteria so that, say, 150 microamperes might be equivalent to a full-scale CDI display from centerline for errors of only 100 feet rather than a nominal 350 feet.

2. HIGH COURSE SENSITIVITY

A high course sensitivity leads to many new questions. Can the pilot fly such a tight course? What happens to the relative values of beam bends, receiver centering errors, etc.? Sometimes localizers are used on takeoff or for an overflight of the runway. It is practical to fly toward the localizer using the CDI to within about 2000 or 3000 feet of the transmitter. This case represents a full-scale sensitivity of about three times that of the current runway threshold sensitivity. This would imply a full-scale deflection of about ±75 to ±125 feet, or a total course sector width of perhaps 250 feet. Some of the newer flight directors use a second CDI needle with higher sensitivity to indicate runway width.

Testing of this set of conditions at threshold would be very informative, since it would theoretically permit much higher approach success. Or, to put it differently, with a 25-microampere pilot display error, the aircraft would always be within the useful width of the runway (assuming an equivalent reduction in guidance errors). It should rarely, if ever, be at or beyond the runway edge upon reaching a decision height of 100 feet. The simulation of higher sensitivities and a commensurate reduction of the major errors contributing to the total error would be most informative.

It is likely that the current ILS accuracy standards will not meet CAT III or perhaps even CAT II limits for several reasons. The simulation would have to examine the relationships of specific errors to piloting and aircraft response. There is some general evidence that dimensions much less than 350 feet for full-scale (or a 700-foot wide sector) could be profitably employed to make CAT II and III-A much more realizable.

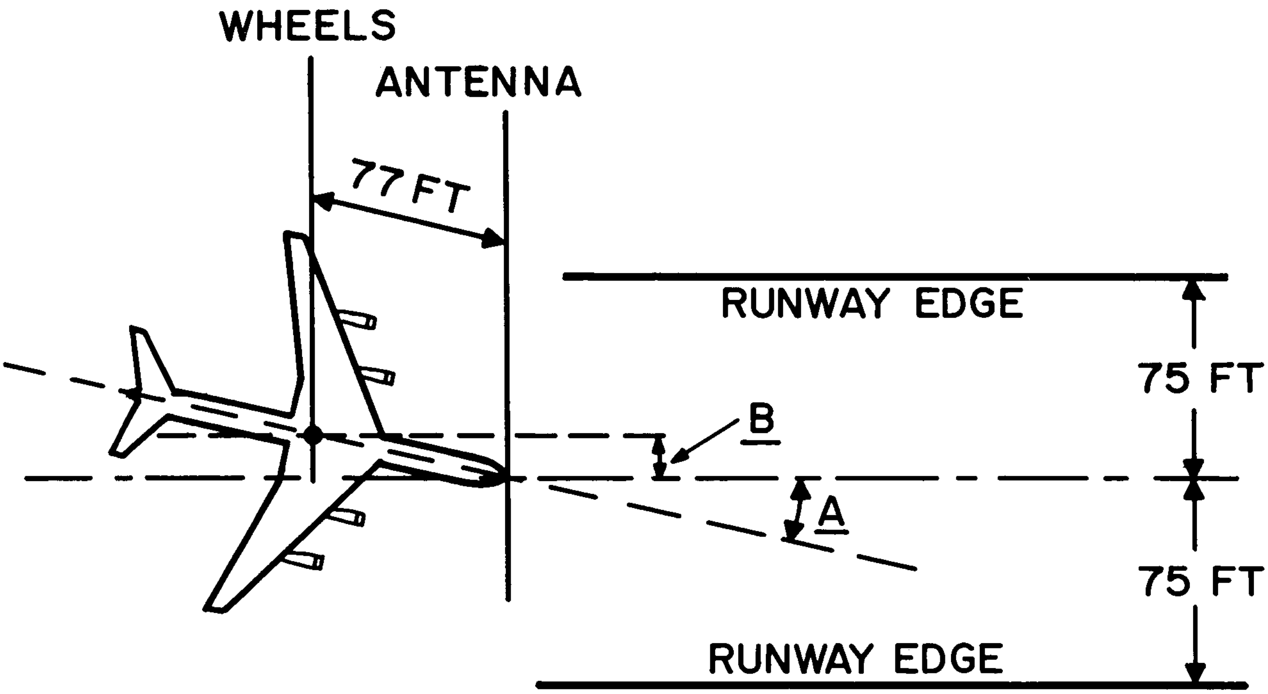
Figure 8 continues the analysis and discussion of localizer course errors emphasizing the threshold area. This is of considerable significance to the CAT III-A conditions since, with only 700 feet RVR (or Slant Visual Range--SVR) little if any time is left for a side-step maneuver. Furthermore, the aircraft is about over the threshold before a segment of surface or visual aids equalling 3 seconds of flight time is available. Three seconds has been used as an estimate. It represents about 600 feet. However, it may vary markedly with speed and aircraft maneuverability. As seen from the cockpit (assume a 14 to 15 degree window cut-off), the 700-foot visual range does not provide a 600-foot segment until the aircraft is below a 40-foot eye level.

This would be a reason that the tolerances, whatever they may be for the 100-foot visual decision height and the 1200-foot RVR (CAT II), should be drastically reduced for the threshold conditions shown in Figure 8 that are representative of a 700-foot RVR. Figures 24, A, B, C, D, show the segments of surface area visible for the pilot. What this segment should be in length for CAT II or CAT III-A is debatable. If one assumes that the pilot needs about 2 seconds for orientation, 1 second to initiate a maneuver, and another second to see the aircraft path change relative to a surface reference point, this requires that the pilot see about an 800 to 900 foot ground segment as a minimum. There are several opinions but little or no measured data on this subject. However, as the aircraft gets closer to the ground, the more the surface segment visible to the pilot is equivalent to the RVR. With height, the pilot loses about 4 times his height in surface visual contact dimension (tangent of 14 degrees). Thus, at 100 feet some 400 feet are lost, leaving only 800 feet (out of 1200) for CAT II and 300 feet for CAT III-A. At 60 feet (eye level) only 460 feet, or slightly more than 2 seconds of time, are left for CAT III-A. The simulation of seeing a 300 to 800 foot long segment of typical surface objects is very important. With various lateral and vertical errors then added by simulation, realistic data becomes available.

3. DETAILED ANALYSIS OF USEFUL RUNWAY WIDTH

Although there are some runways 200 feet wide, the majority of major U.S. runways (say JFK) are only about 150 feet wide--the ICAO minimum width. The localizer antenna is usually mounted in the center of the nose or tail of the aircraft to provide symmetry of centerline guidance. However, the pilot must not land with any of the aircraft wheels off the paved surface. Assuming that the outside dimension between the two outside wheels is about 27 feet (and may be greater for larger aircraft), this amount of runway as a minimum is lost. Another significant error in lateral dispersion not always noted is that due to crab angle. Since there is a considerable distance between the nose (or tail) and the main gear, the aircraft can be indicating a deviation error during crab that is not representative of the wheel position. This is not serious until the aircraft is over the threshold. But, once the pilot has passed the threshold, it is another error he must consider before touchdown, if he is off center. Figure 9 illustrates that for a typical operational aircraft this amounts to about 7 feet for a 5-degree crab angle. For 10 degrees it is about 14 feet. With allowable cross winds, heading corrections, and typical approach speeds, these values are within operational limits.

Figure 10 combines the crab angle and gear-width restrictions to show that some 25 feet are lost on either side if one assumes that the cross wind will be from either side. This combination alone effectively reduces a 150-foot runway to 100 feet. For long aircraft this can be a greater reduction. If, for example, a cross wind exists calling for a crab angle of 6 degrees, and the pilot is turning toward the course in a normal bracket or side-step maneuver with a 4-degree additional heading angle, the 10-degree figure is readily generated. Thus, with this logic, the useful runway width is reduced by 33%. The useful width of only 100 feet for most ILS runways is further



CRAB ANGLE A	WHEEL DISPLACEMENT B
5 DEG.	7 FEET
6	8.2
7	9.5
8	10.7
9	12.0
10	13.2

FIGURE 9

ERROR CONTRIBUTED BY CRAB ANGLE FOR 707 CLASS AIRCRAFT

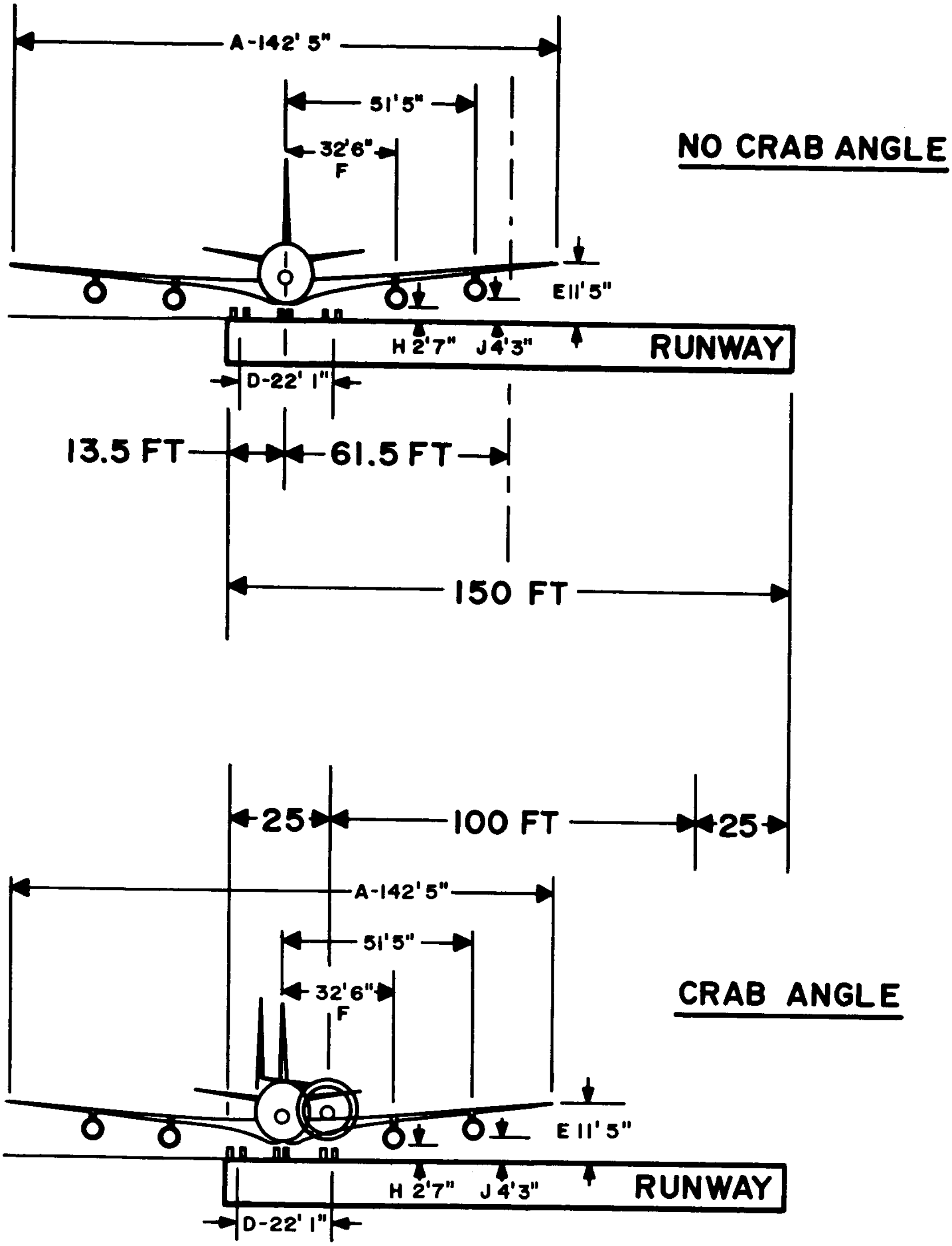


FIGURE 10

EFFECT OF MAIN GEAR WIDTH AND CRAB ANGLE ON USEFUL RUNWAY WIDTH (TYPICAL RUNWAY WIDTH AND NOSE-MOUNTED ANTENNA) reduced by guidance errors to sometimes as little as 5 to 10%, or a mere 10 feet. Figure 11 further illustrates this point and allows another 5 feet on either side for a "buffer" or additional tolerance for the pilot. This then reduces the effective useful width of the runway to about 90 feet. If a 10- or 15-foot "buffer" is considered, this effectively reduces the width to as little as 70 feet. This makes the errors of Figures 5 through 8 far more significant. Additional runway width is not likely to be available in the near future.

4. POLARIZATION ERRORS

When an aircraft banks, the VHF antenna polarization is changed due to the bank angle of the aircraft. The ILS system is horizontally polarized; however, the maintenance of pure polarization in the ground antennas and aircraft antennas is difficult in the VHF spectrum. ICAO allows (3.1.3.2.2.1 of Annex 10) a DDM error of 0.008. Since full-scale lateral deviation is 0.155 DDM, this is approximately 8 microamperes of CDI display for a bank angle of 20 degrees. If this were a linear function, which it may or may not be, a 10-degree roll limit would limit this to a 4-microampere error. This error may not be easily treated statistically since it is highly correlated with lateral errors and cross wind. In a given landing condition these may all add arithmetically. However, the total is somewhere near that allowed for course bends; therefore, for estimating, this figure can be used to include the polarization effect.

A given course bend may create a bank angle, resulting in a polarization error which, when added to a steady-state cross wind, can create system errors that do not follow a normal distribution. In such cases the errors may add arithmetically, and the total can then be treated statistically with the several other errors. A simplified example follows:

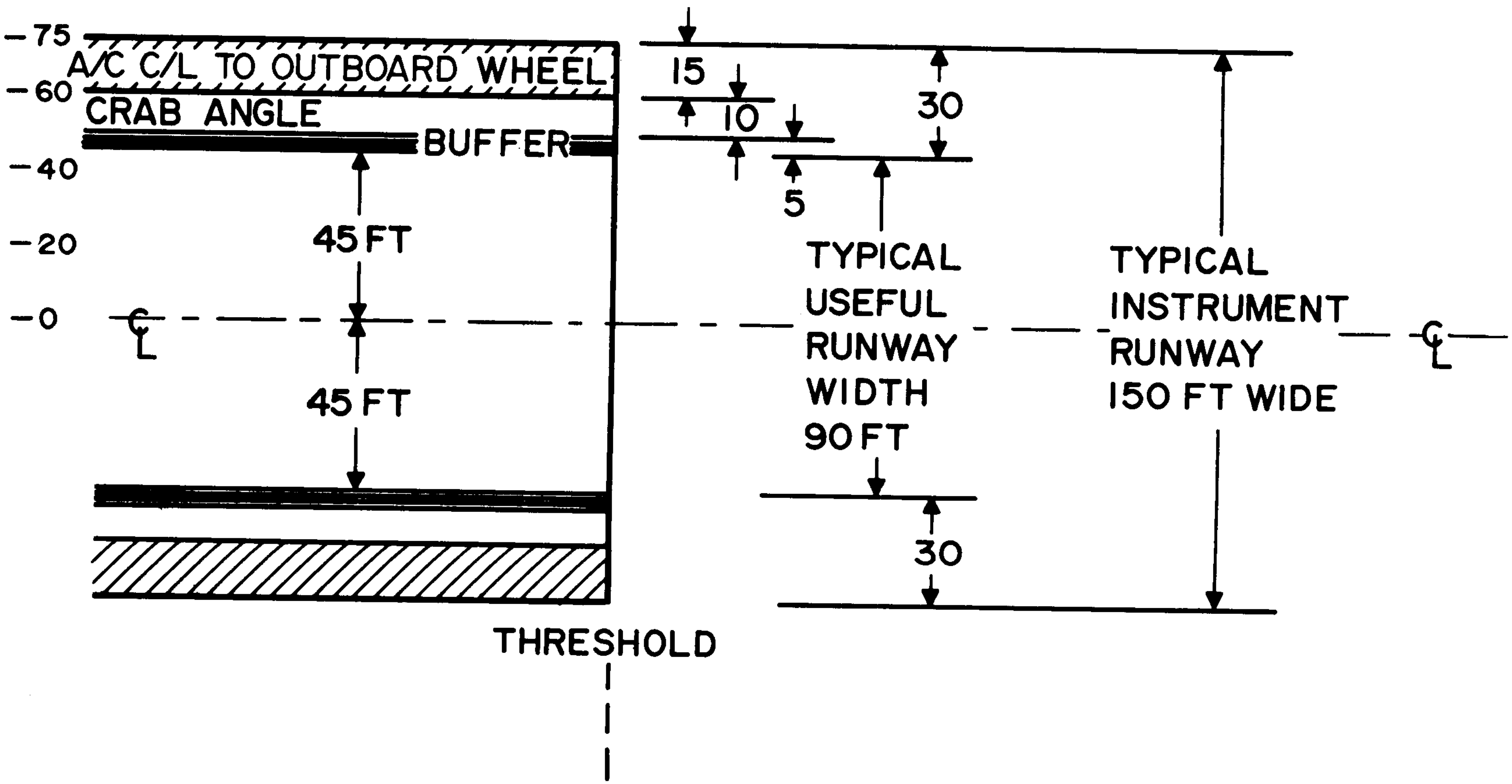


FIGURE 11

SIXTY-FOOT REDUCTION IN USEFUL RUNWAY WIDTH FOR A LARGE JET
(SEE ALSO FIGURES 9 AND 10)

Localizer beam bend error at 100-foot height	22 feet
Polarization error during beam correction (10-degree bank)	18 feet
Crab angle error	12 feet
TOTAL (arithmetically added--not RSS) error	52 feet

One could then assume this as a 3 sigma error and treat the other errors on an RSS basis: $\sqrt{52^2 + 28^2 + 43^2 + 104^2}$ of Table I. This gives an RSS figure of 127 feet instead of 117 feet. The usual diminution of errors treated in this manner is a clear case for questioning the use of normal statistical treatments without more measurements to determine the validity of this mathematical approach to a flight risk perhaps a thousand times greater than the flight risks associated with current practice.

5. RELATIONSHIP OF LOCALIZER ERRORS AND USABLE RUNWAY WIDTH

Figures 12 and 13 combine many of the previously developed error curves into a single presentation. To examine the individual errors, one must refer to Figures 1 to 11. It can be seen in Figure 12 that the two and three sigma lines are represented as well as the worst case. These are approximate probabilities of 50/1000, 3/1000, and (perhaps) 1/10,000, respectively. The probability of the worst case is only estimated at present, since pertinent measurements are lacking. Extensive measurements and statistical treatment as to the nature of combining low visibility errors are urgent needs. Here is a case where the human error and aircraft response limitations of following the indication (this must also be allowed for any automatic flight control) must be carefully assessed. The specific errors may not be combinable in the usual statistical sense, since they are independent or related in manners not amenable to the simple RSS (square root of the sum of the squares) treatment. Skewness of data due to wind shear, course bends, instrument biases,

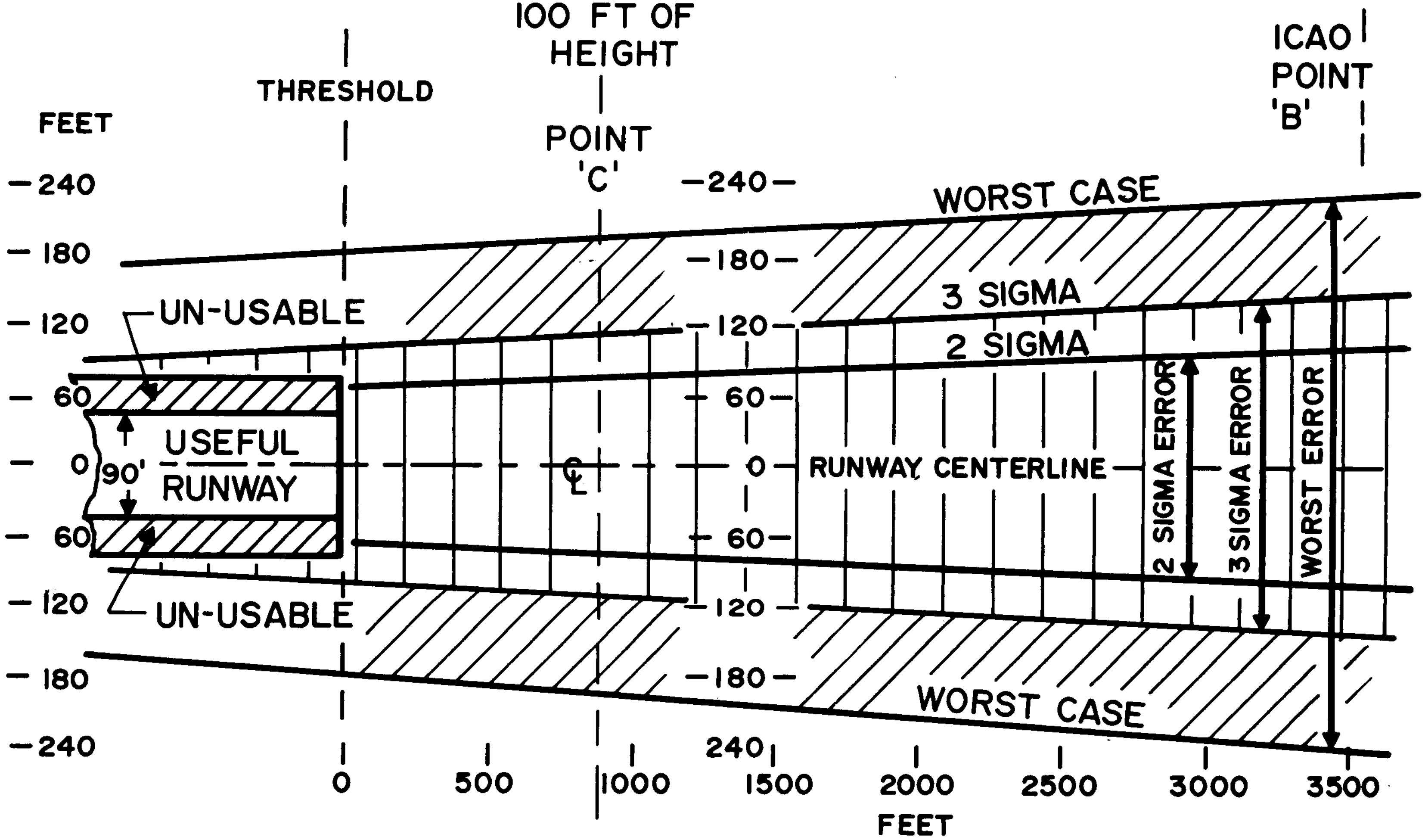


FIGURE 12

RELATIONSHIP OF LOCALIZER AND PILOTING ERRORS
WITH RESPECT TO USEFUL RUNWAY WIDTH (ICAO-AC-120/20)

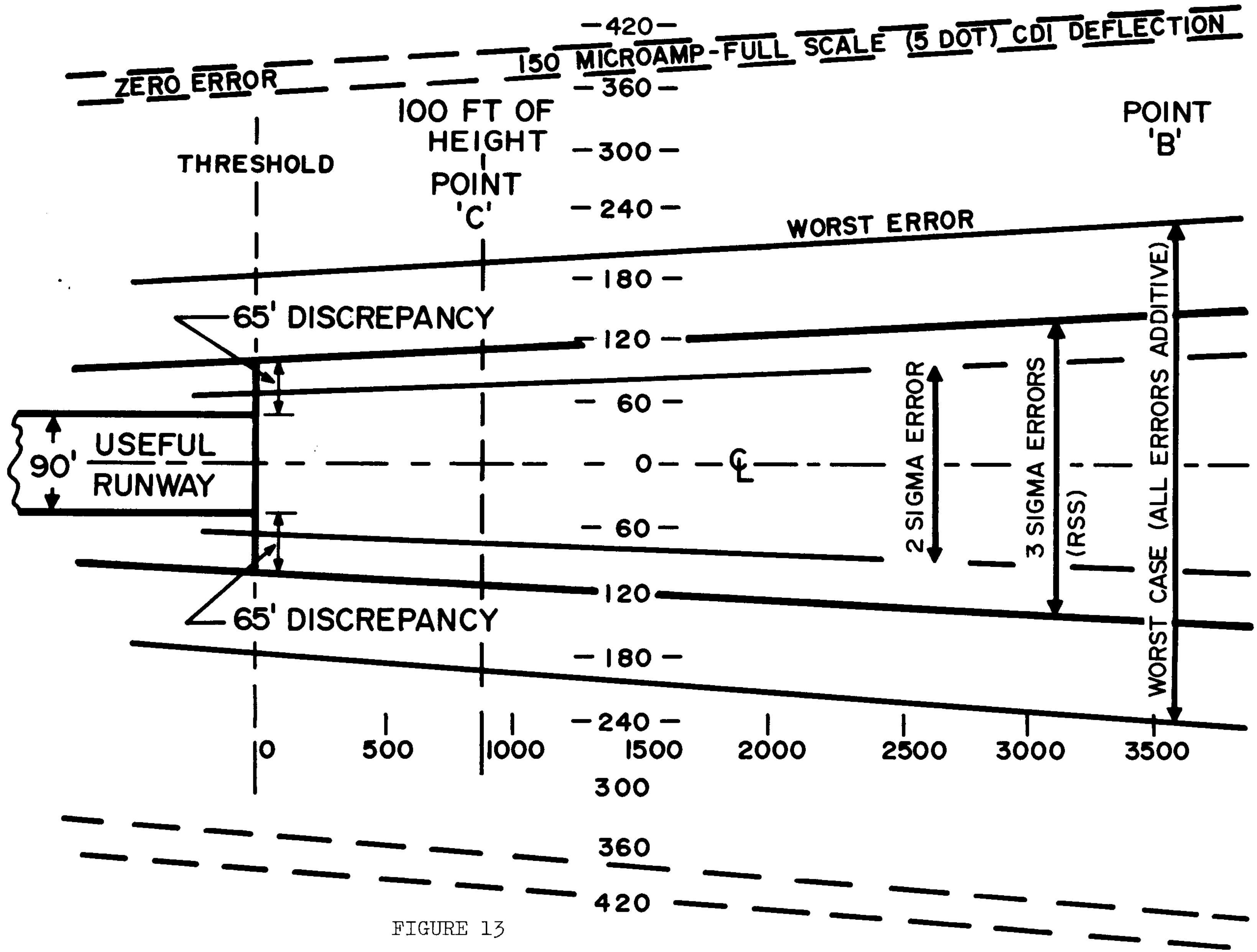


FIGURE 13

THRESHOLD DISCREPANCIES

non-linearity of beams can, for a combination of an individual runway and aircraft, be far from a normally distributed error and can add--for the specific landing in question arithmetically approaching the worst-case.

There is no denying that the worst-case contour has some statistical significance. Only detailed measurements will establish whether it is a probability of a 1/1000, 1/10,000, 1/100,000, or perhaps greater. Furthermore, the piloting accuracy to a 25-microampere accuracy under conditions of wind shear, stress, following bends, poor instrument sensitivity (e.g., on an ID-249 the needle motion is only about 1/8 inch for 25 microamperes).

Figures 12 and 13 illustrate an important point; that the outside visual cues and the pilot's instrument display cues for vertical and horizontal guidance can differ radically. The discrepancy of cues is much more obvious for lateral guidance. For example, if the pilot is off the runway centerline by 75 feet he will be aligned with the edge of the runway, a very obvious, major displacement. The runway edge would appear to be a straight line in front of him, whereas the other edge would be at a rather large relative angle. This also depends upon the exact distance. At greater ranges in VFR with the same lateral displacement, the relative angles made by the two sides of the runway create overwhelming visual cues. However, in low visibility landing, when the pilot first sees these startling cues he is too close for his normal VFR corrections to be applied.

The main point of the foregoing is that the pilot can sincerely believe he is doing a good instrument-following job, yet be severely shaken when visual surface contact is made by how much he can be off. Many so-called "Heads-Up" displays are designed to provide the pilot a simulated perspective display of the runway. The rules of perspective are employed to generate the geometry of the scene. However, if the displayed runway perspective is driven from the ILS localizer signals the aggregate electrical errors of the system will cause the image to appear geometrically displaced from the actual runway, which is also partially visible by as much as 55 feet. As seen in Figure 14, this could be quite distracting to the pilot.

Another point to be discussed in the section on vertical guidance is that there is no correlation from one runway to the next with regard to distance of the glide path emitter, angle, or threshold height which further distorts any pictorial or graphic "Heads-Up" display with respect to the actual, real world, when seen (even partially) by the pilot. (Figure 14)

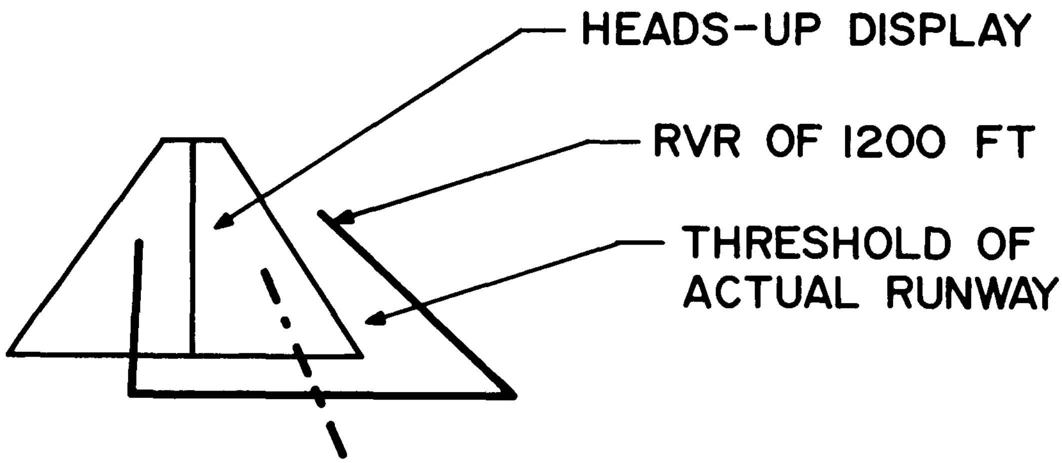


FIGURE 14

DISTORTION INTRODUCED BY HEADS-UP DISPLAY
(AS SEEN BY PILOT) WITH REFERENCE TO REAL WORLD

Figure 14 assumes that the pilot is flying an ILS-guided course with a perfectly aligned display in range and vertical angle (neither case being likely in practice). More examples will be given of typical vertical and longitudinal errors wherein thresholds and perspective lines disagree far more than this case.

Figure 15 combines the full-scale deflection (if no error existed in the radio guidance), the 2 and 3 sigma errors, and the worst case. It will be noted that there can be a lateral error of 110 feet, placing the outer wheel 65 feet beyond the useful runway width for the 3 sigma case. Figure 15 illustrates the CDI indication required to stay within the useful lateral runway dimensions that remain (less than 10 to 15 feet) after guidance errors are employed to simulate this effect. Even the 2 sigma error places the outer wheel about 30 feet beyond the edge of the useful runway, being about 73 feet off centerline. The aircraft center is nearly on the edge of the actual runway in the 2 sigma case when the aircraft passes over the threshold.

Since it is obvious that the 3 sigma values can reduce the "useful" runway width to a meaningless value (less than zero), Figure 16 illustrates the results of only 2 sigma errors (50/1000). The remaining useful runway in this example is about 22 feet, assuming that no pilot error or flight errors exist. This uses the crab angle, gear width, and the 2 sigma RSS values of only the localizer signals. Since these add to 64 feet (30 + 34), this leaves but 11 feet for allowable error off centerline. In terms of CDI deflection, this is 11/350 or 3% which is about 5 microamperes of flight error (not 25 microamperes as in AC 120-20). To emphasize this point, the lower half of Figure 16 illustrates a runway that has been widened to accommodate the 2 sigma errors of flight, guidance, and the crab angle/gear dimensions. This would be an example of the width required to assure that the outboard main gear wheel is at least 5 feet within the edge of the paving of the runway. In cases of automatic localizer flying,

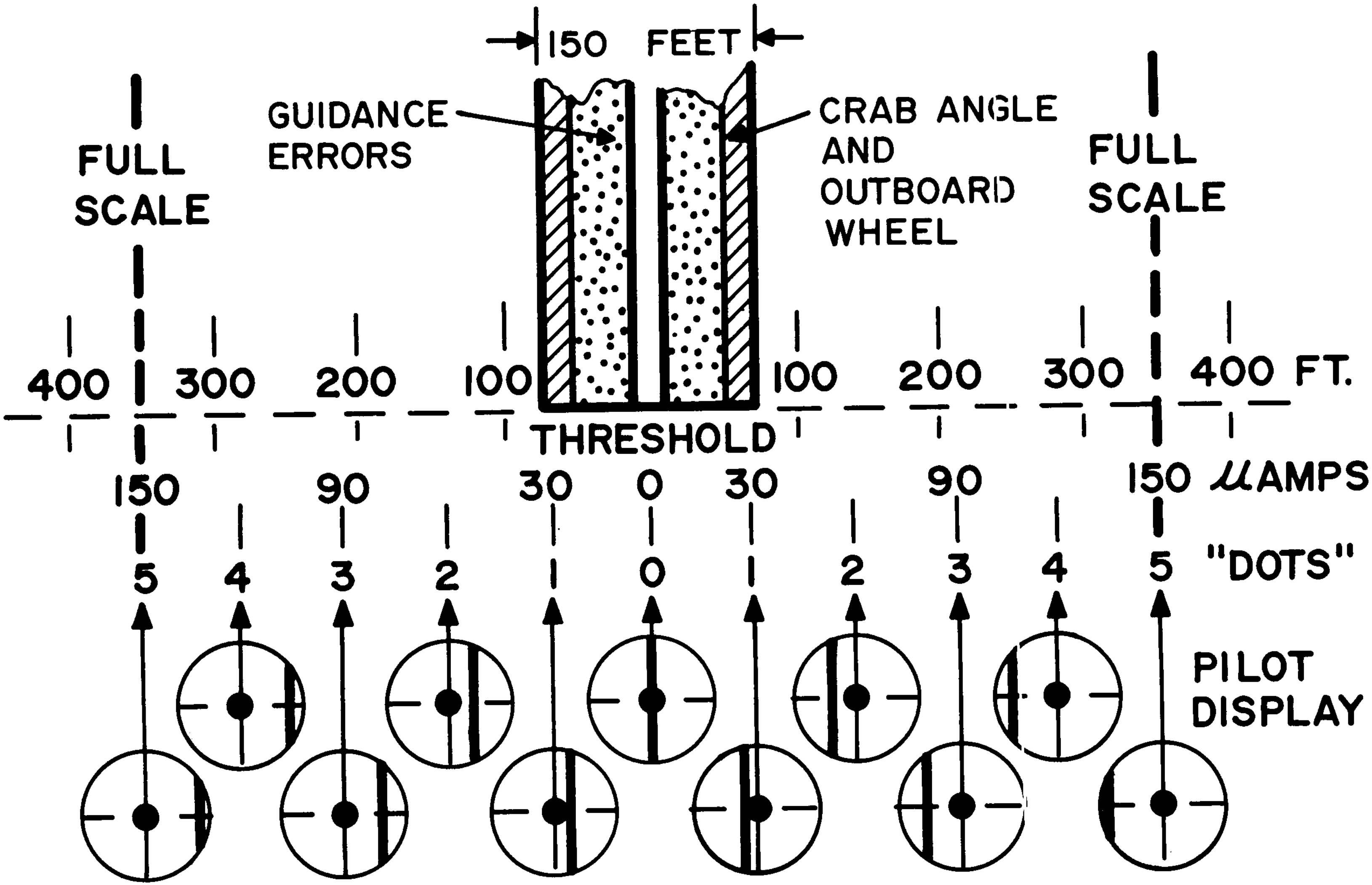


FIGURE 15

ICAO/ILS STANDARD FOR ILS SENSITIVITY RELATED TO 3 SIGMA (RSS)
ERRORS OF GUIDANCE, CRAB ANGLE, AND WIDTH OF MAIN GEAR

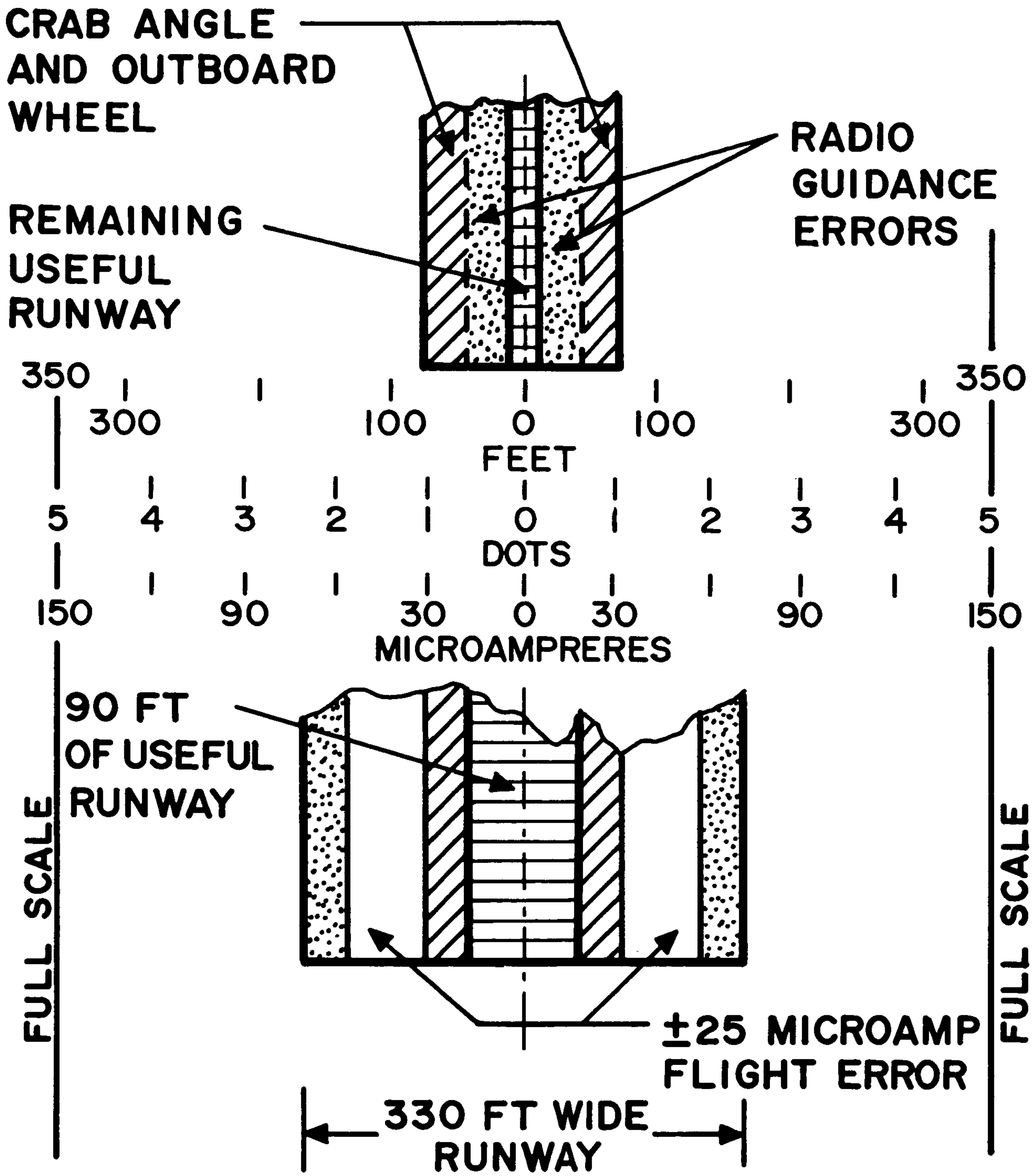


FIGURE 16

RELATIONSHIP OF GUIDANCE AND FLIGHT ERRORS TO RUNWAY WIDTH (2 SIGMA) where it is permissible to pass threshold automatically coupled to the radio guidance, such runway widths (330 feet) are required for about a 2 sigma case. This implies that some 50 cases out of 1000 cases will not achieve this. Since one wheel off the runway paving can be catastrophic, this is obviously too high a risk and a wider runway is indicated.

Figure 17 assumes that a pilot would like to be within 45 feet of centerline or, to put it differently, that he is safe if he is within 45 feet of centerline. The errors are added in two ways to the "useful" 90-foot wide runway, showing that between 380 to 440 feet of width is needed if the current ILS localizer standards are utilized in CAT III.

Some experts suggest that the pilot will not touch down unless he is within 30 feet of centerline to allow for cross-track velocities (lateral drift rates) just prior to and at the time of touchdown (due to wind, heading errors, or a faulty de-crab maneuver). This would imply for runways ±75 feet wide a lateral side-step maneuver of about 80 feet starting at the threshold for CAT III (3 sigma). The time for flight track correction (to accomplish this amount of lateral change with the severe limitations on bank angle) at this low wheel height (20 to 40 feet over threshold) could be about 30 to 40 seconds. This is about 6000 to 8000 feet of forward flight, obviously resulting in an incompatible situation with the sink rate and runway length criteria normally used.

Although all aircraft are not this limited in bank angle, the large aircraft used by the airlines are typified by Figure 18. Here it is seen that an angle of only 6 degrees exists between the outboard engine pod and the main gear. This, of course, is a "never-exceed" figure so that limits of perhaps half this value, or around 3 degrees should be employed in any very low visibility roll angle and roll rate calculations.

Piloting techniques and opinions differ considerably

THREE SIGMA VALUES

A	USEFUL RUNWAY WIDTH 90 FT OR	±45 FT
B	CRAB ANGLE AND MAIN GEAR	±30 FT (JUMBO JETS)
C	FLIGHT ERROR (AC 120-20)	±97 FT (37.5 MICROAMP)
D	RADIO GUIDANCE ERROR	±50 FT (RSS OF 3 ELEMENTS)
F	COMBINED (RSS) FLIGHT AND GUIDANCE ERRORS	±110

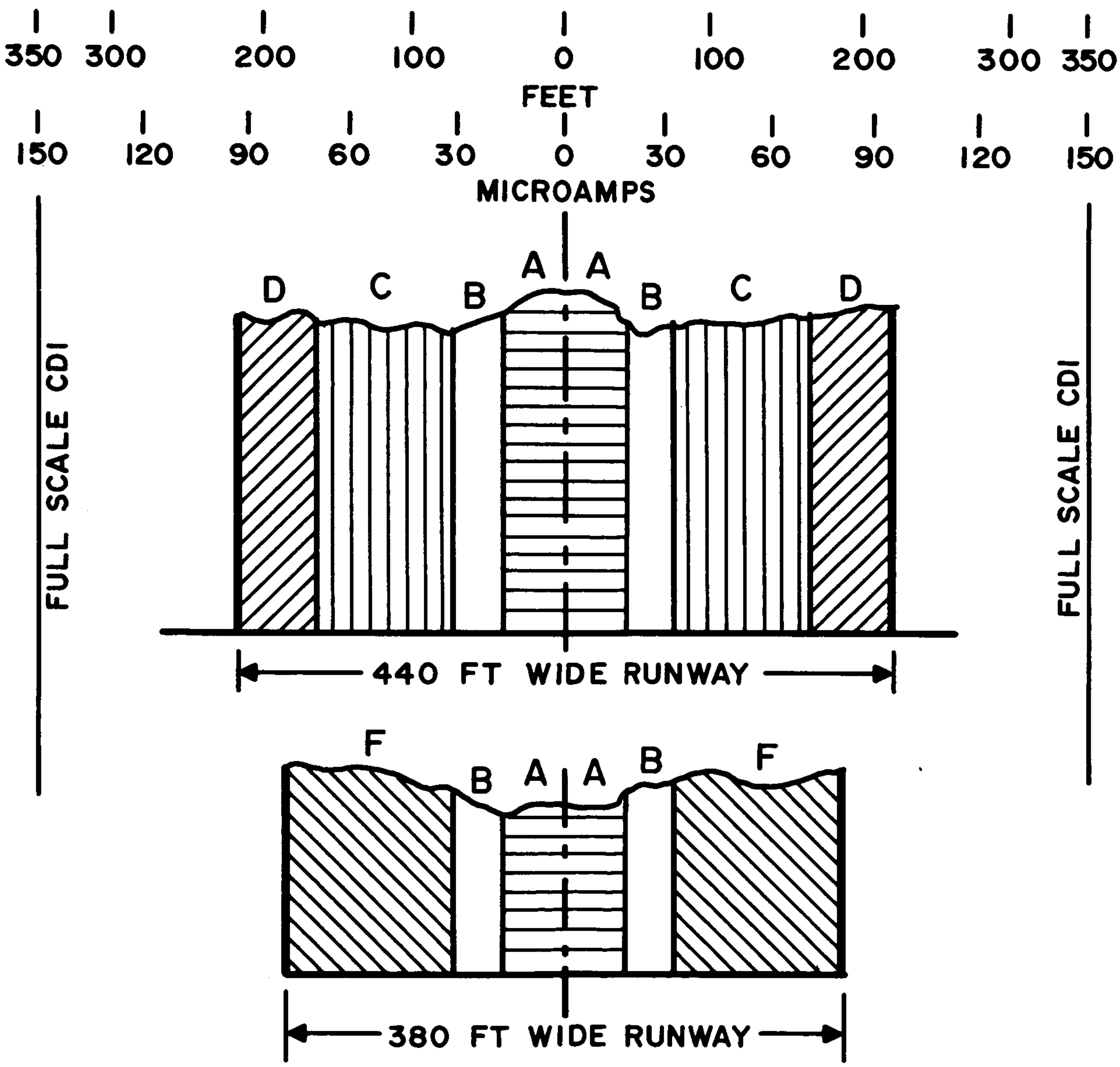


FIGURE 17

RELATIONSHIP OF GUIDANCE AND FLIGHT ERRORS
TO RUNWAY WIDTH (3 SIGMA)

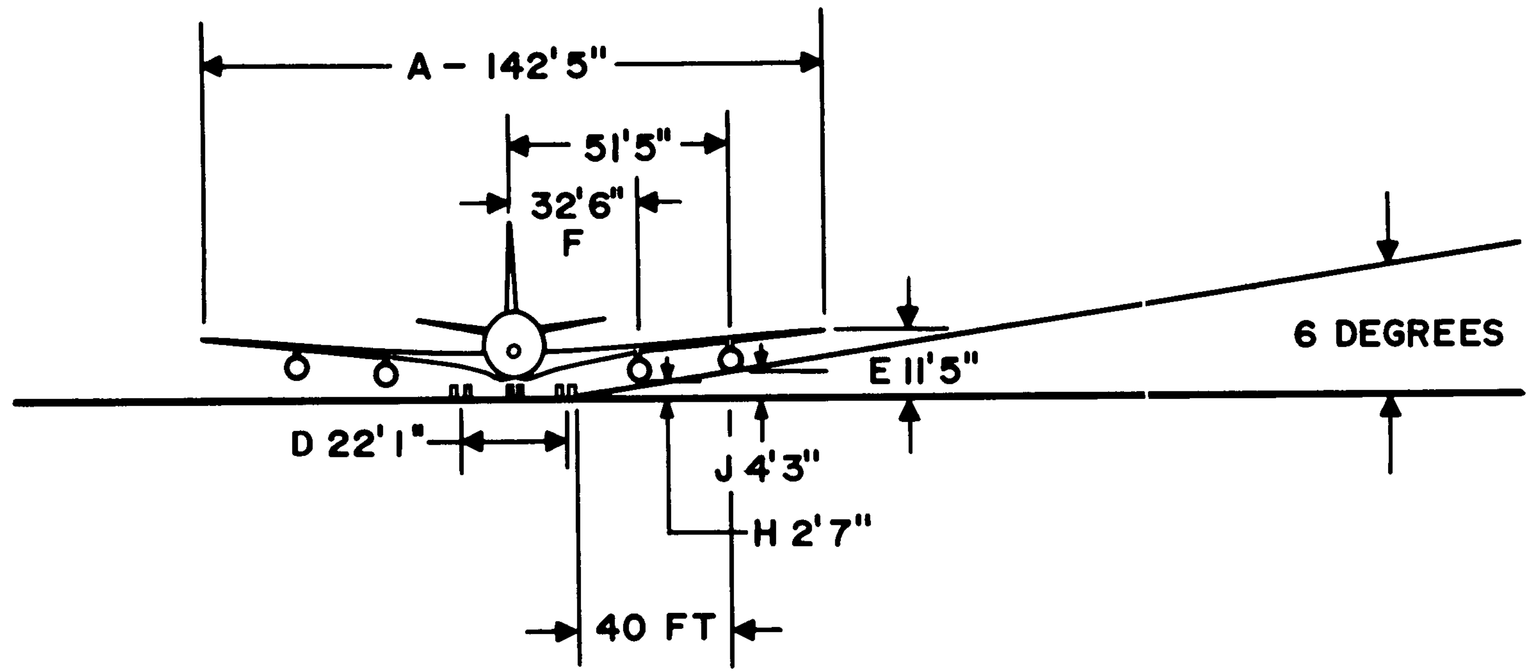


FIGURE 18

NEVER TO BE EXCEEDED BANK LIMIT
OF FOUR-ENGINE JET TRANSPORT

on this point, some pilots preferring a wings-level correction and others preferring a side-slip including some bank. This is obviously an area needing further investigation, since it is highly significant in view of the ILS error analysis and quite amenable to measurements.

6. MEASURED FLIGHT ERRORS

Data taken in the United Kingdom and reported in the International Transport Association report (Lucerne meeting) of May 1963 indicates that these figures are generally encountered in practice. For example, Figure 5 of this IATA paper indicates that lateral errors at a point 1000 feet from threshold (2000 feet from a typical glide path emitter-antenna) are around 100 feet for the 2 sigma case (two standard deviations) and 150 feet for the 3 sigma cases. Although it appears as rather sketchy data, it was taken with an automatic ILS-coupled aircraft, so that presumably all systematic errors are adding in various amounts and directions in the data. This agrees with Figure 7 of this report, for example, which shows an RSS 3 sigma value of 117 feet and 194 feet for the worst case.

Interestingly enough, the mean value presented in ICAO WP-142 at a 3500-foot distance from threshold (Point B) is about 250 feet for the 3 sigma case, whereas Figure 6 of this report estimates it at 143 feet for the 3 sigma case and only 236 feet for the worst case. Since piloting (manual or automatic) is the largest error, this may indicate that in these two cases the 25-microampere figure for maneuvering laterally is being exceeded. Additional errors not considered here may also exist.

7. AREAS NEEDING FURTHER ANALYSIS AND MEASUREMENT

Before leaving the lateral guidance problem involving the errors of the ILS-localizer and the limitations encountered in attempting to reduce them by maneuvering large jet aircraft near the ground, some specific areas need identification for further attention:

1. The roll angle and roll-rate limits of various aircraft distance to make lateral or side-step maneuvers of around 100 feet, and piloting techniques to accomplish these maneuvers when below a decision height of 100 feet need a far better measurement analysis and documentation than now exists for current heavy jet transports and bombers.

2. These studies should be extended to the large aircraft dimensions and performance of such aircraft as the 747, SST, and C-5A to determine the extent of any differences.

3. Detailed simulations and flight measurements should be made of typical pilot deviation from a localizer course, assuming initially a straight course and then one with bends as described by ICAO; the conditions of variable cross-wind, maximum constant cross-wind, and wind shear should then be added. Most data today is based on slow, piston aircraft in relatively smooth air. From this it should be established if 25 microamperes for a 2 sigma case at ranges of less than 3500 feet from threshold are reasonable without outside visual references. Should the figure be changed? What values would be associated with specific aircraft types?

4. Tests with typical runway perspective displays should be made (that is, "Heads-Up") to determine the extent of the visual non-registry problem.

5. Simulations should be undertaken of several dual pilot techniques for the low visibility lateral correction. Three identified (pilot-first officer) landing techniques exist (BEA, Aero-Postale, ALPA). The transition between two pilots, between instrument and visual flight control for specific side-step maneuvers and under real or simulated low-visibility conditions needs far more quantitative data than exists on this "team" type or dual pilot effort. The level of the First Officer's experience is highly significant under current regulations, which require primarily that only the Captain be qualified for low visibility landing.

6. Examine, by increasing the specific amount of lateral side-step maneuver (within the expected tolerances, herein discussed), the point at which an aborted or missed approach should be executed rather than a side-step maneuver. Although this may be defined by computer analysis, a level of human judgment is involved; furthermore, time delays for the exercise of this judgment and the amount of ground track required for establishing

the required heading will determine this in practice. It may differ markedly from previous computerized studies on the subject, since these pertinent delays essential to safety were not introduced. It has been estimated in ICAO WP 142 that it takes a total of 7 seconds for a pilot to: (1) "integrate" the information from the restricted visual sector, (2) apply a corrective action, and (3) for the aircraft to move laterally a few feet. Of course, several seconds are required for the lateral error to reduce, assuming lateral rates of 2 to 3 feet/second.

7. During this lateral correction, of course, the sink rate can be around 12 fps, unless arrested by adequate vertical visual guidance cues. Consequently, over 80 feet of height can be lost in this action alone, before the aircraft starts to make a major lateral or side-step correction. This adds to the pilot task of lateral correction, since the vertical correction must be initiated during the 7 seconds of time, requiring measurements of two simultaneous precision maneuvers.

8. A set of tables or graphs should be generated involving variables of lateral error (in 10-foot amounts from 0 to 150 feet), bank angle (in ½-degree steps to 5 degrees), airspeeds (from 100 to 200 knots in 10-knot steps, including many military aircraft), cross-wind, and allowable useful runway width (from 25 to 45 feet in 5-foot increments). Such tables or graphs would admittedly total hundreds of pages but would prove invaluable to the many electronic designers of landing systems and equipments, as well as ICAO committees, etc.

9. The value of the current lighting system for alignment should be determined when obtaining initial visual contact at 200-, 150-, 100-, and 50-foot eye levels. In many cases, the approach lights will be visible for less than 5 seconds at best, and in some 3 sigma cases for only 1 second. What amount of information can be gained from such a short exposure? This will require very skillful simulation with lateral errors. What new lighting configurations would be useful for such large lateral corrections and short observation times? Does directivity of lights cause difficulty at large lateral displacements?

E. VERTICAL GUIDANCE

Figure 19 introduces the vertical guidance aspect of the landing guidance parameters by illustrating the new criteria for glide path location. The concept of the threshold height being a focal point for the electrical path criteria is new and is essentially approved by dozens of countries (including the United States) affiliated with the ICAO organization and its aviation Standards. The Standards call for the electrical path (not the wheel path) to be at a height of no less than 50 feet, with an upward tolerance of 10 feet (to 60 feet) and no downward tolerance for CAT II and III. Although several combinations can exist to achieve this within the limits of 2.5 and 3.0 degrees, they all appear to fall within the limits of threshold distances shown in Figure 19. The distance from threshold for a critical height such as 100 feet obviously is quite variable. It will be seen that the nearest case for a 100-foot height is around 770 feet, and the most distant case, also for a 100-foot height, is around 1150 feet. This assumes that no errors exist. The difference of about 380 feet is highly significant to the pilot, aircraft instrumentation, and operation.

The emitter or path origin point is seen to also vary somewhat, but is approximately 1150 feet from threshold. The distance variation for point C, about 50%, significantly modifies visual cues needed for landing. For example, assuming the cockpit cut-off angle of about 14 degrees does not vary, the pilot flying on-course at a point 770 feet from the threshold will see but 370 feet of approach lights. This allows but a 1.8-second glimpse of the lights, prior to their passing out of view.

This can be less as will be noted when we examine the vertical guidance tolerances in the same manner that we examined the lateral guidance tolerances.

Figure 20 treats the glide path errors in a manner quite similar to the localizer errors. One significant difference

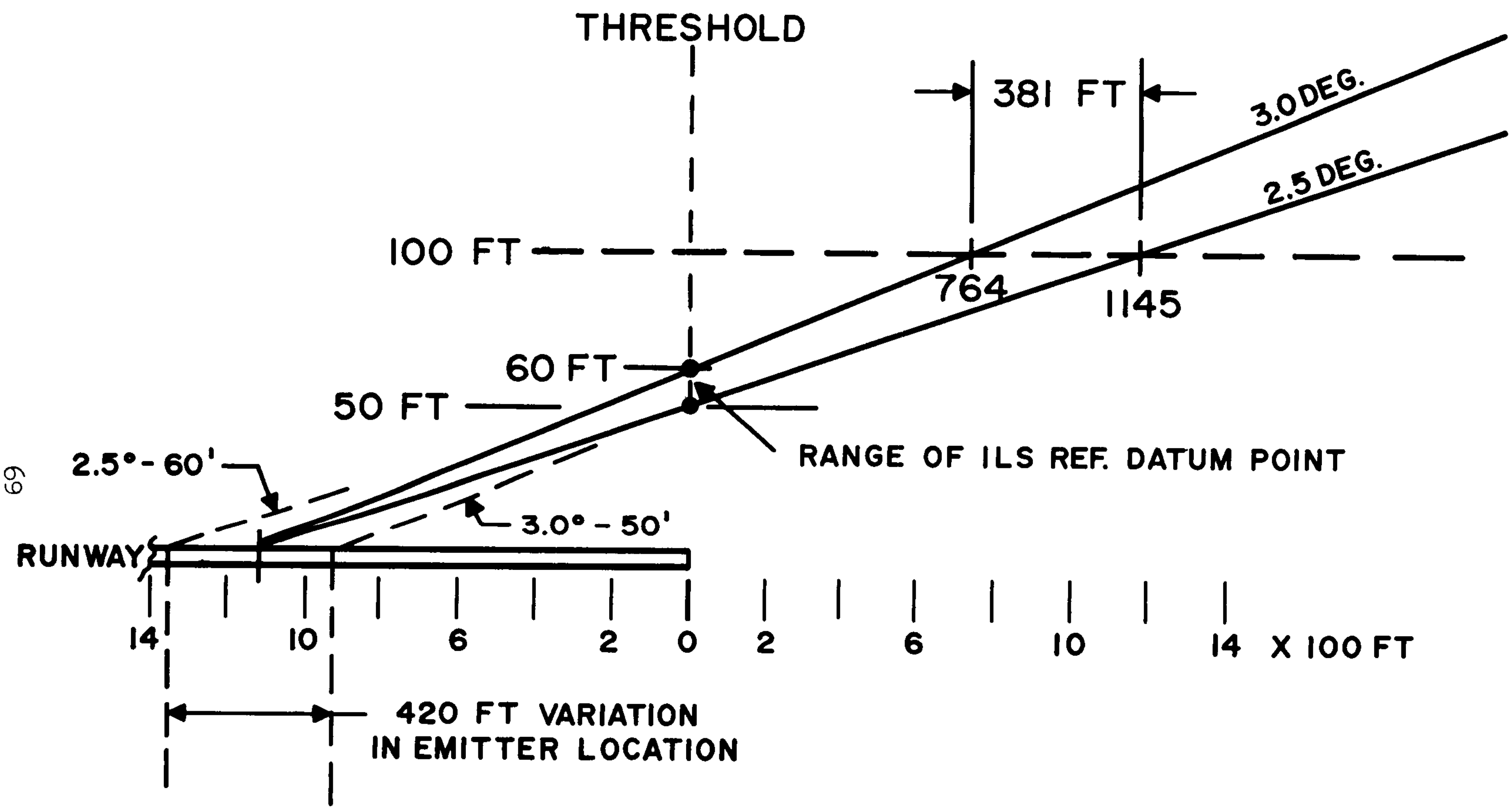


FIGURE 19

VARIATION IN GLIDE PATH ANGLE AND PATH HEIGHT OVER THRESHOLD FOR CAT II

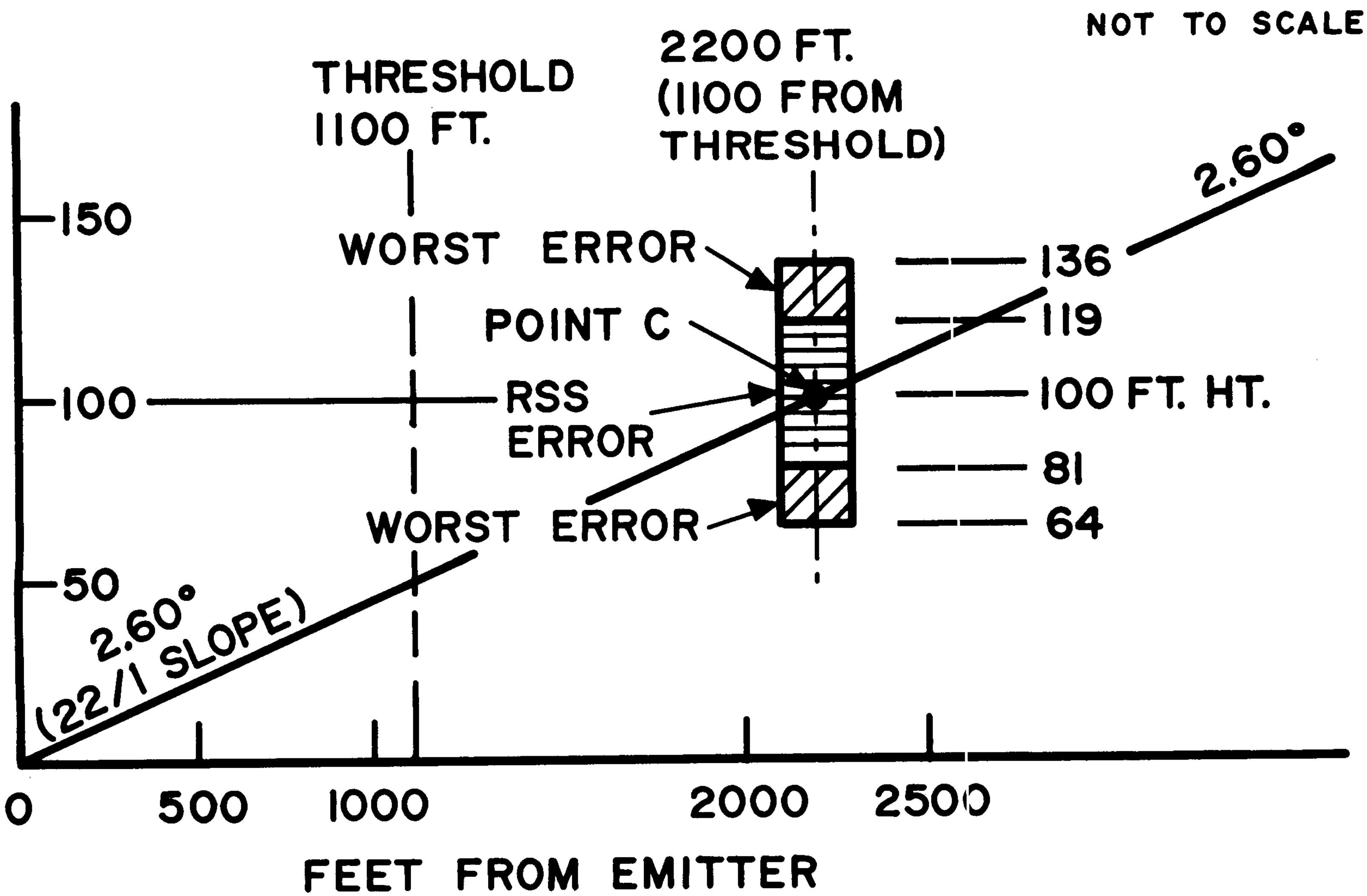


FIGURE 20

GLIDE PATH GUIDANCE ERRORS (INCLUDING PILOTING)

<u>3 SIGMA VALUES (ICAO) AT 100 FT. HT.</u>

(3.1.4.6.1) Course Shift (0.2 degree)	8 ft.
(2.1.5) Beam Bends (±20 Microamperes-2 Sigma)	5 ft.
(2.2.5.1) Receiver Centering (27 Microamperes).	5 ft.
(3.1.4.5.4.7) Linearity (20%)	
AC 120-20 Flight Error 35 Microamperes or 12 ft. . . .	12 ft.
Total Maximum Error 30 ft. (+20%)	36 ft.
RSS Error 16 ft. (+20%)	19 ft.

is that the flight from a distance of 3500 feet (before threshold) to threshold will have a much larger change in course sensitivity than the change in localizer course sensitivity. This is true because the glide path transmitter is located near touchdown, whereas the localizer is at the distant end of the airport. While the glide path sensitivity changes by 400% from point B to threshold, the localizer changes less than 40%--a ten to one difference. The normal glide path sensitivity is in the region of about 0.70 degree to 0.80 degree for full-scale deflection of the path as displayed by the CDI. The ICAO tolerances are as follows when observed at point C or at a 100-foot height:

TABLE II

ICAO Reference	Characteristic	Value	3 Sigma Conversion
3.1.4.6.1	Course shift	±.075 x angle for CAT II	8 feet
2.1.5	Beam bends	±20 microamperes 2 sigma	5 feet
2.2.5.1	Receiver centering	±9 microamperes 1 sigma	5 feet
3.1.4.5.4.7	Linearity(20%)		Applied to all
AC 120-20	Flight error	±35 microamperes or 12 feet	12 feet

The total maximum error is 36 feet (using the 20%) and the RSS error is 16 feet. When applying 20%, this RSS becomes 19 feet. Assuming the aircraft is at a height of 100 feet, it will be approximately 2200 feet from the intersection of the glide path and runway. This assumes only a nominal glide path angle of 2.60 degrees. With the errors added, the upper height could be 119 feet and the lower 81 feet for the 3 sigma case. For the "worst-case" the dispersion of height error at this same distance could be between 64 feet and 136 feet. When it is suggested that range and vertical angle be used for computing height, it is obvious that some large errors can be encountered occasionally, because the cotangent values change at a high rate for vertical angles below 3 degrees.

Figure 21 is more operationally significant, since it indicates the longitudinal spread of point C, 100 feet of height, that will be encountered when the errors are added to both sides of the glide path course. It will be seen that these errors convert to wide changes in the distance from threshold for the 100-foot point. For example, the arrangement of glide path shows the 3 sigma dispersion totaling about 900 feet, about a point only 1100 feet from the threshold. The nearest distance for the 100-foot level (point C) is 740 feet from the threshold and the greatest distance is 1660 feet. This indicates that the longitudinal dispersion is not symmetrical, but that it can amount to shifting the 100-foot point 360 feet toward the threshold and about 560 feet back from it, for a total dispersion of 920 feet (about a nominal path).

The worst case has a dispersion of almost 1700 feet with the nearest point being only 500 feet from the threshold. This case would cause the pilot to see but a 100-foot segment of the approach lights, about ½ second of flight, assuming a cockpit cut-off of about 14 degrees.

To include all the variations that will add to the longitudinal dispersion of the 100-foot point, it is also necessary to add the variation of glide slope angles and threshold height conditions noted in Figure 19. A simple case is illustrated in Figure 22 in which the 3 sigma errors are added on the upper side to a 3-degree path; and similarly 3 sigma errors are added below a 2.5-degree path. It will be seen that this creates considerable additional longitudinal dispersion, increasing the spread for the 3 sigma errors and the path angle variation to around 1200 feet. The influence of altimeters is noted since they can contribute further dispersion. Such errors are significant but will not be treated in detail.

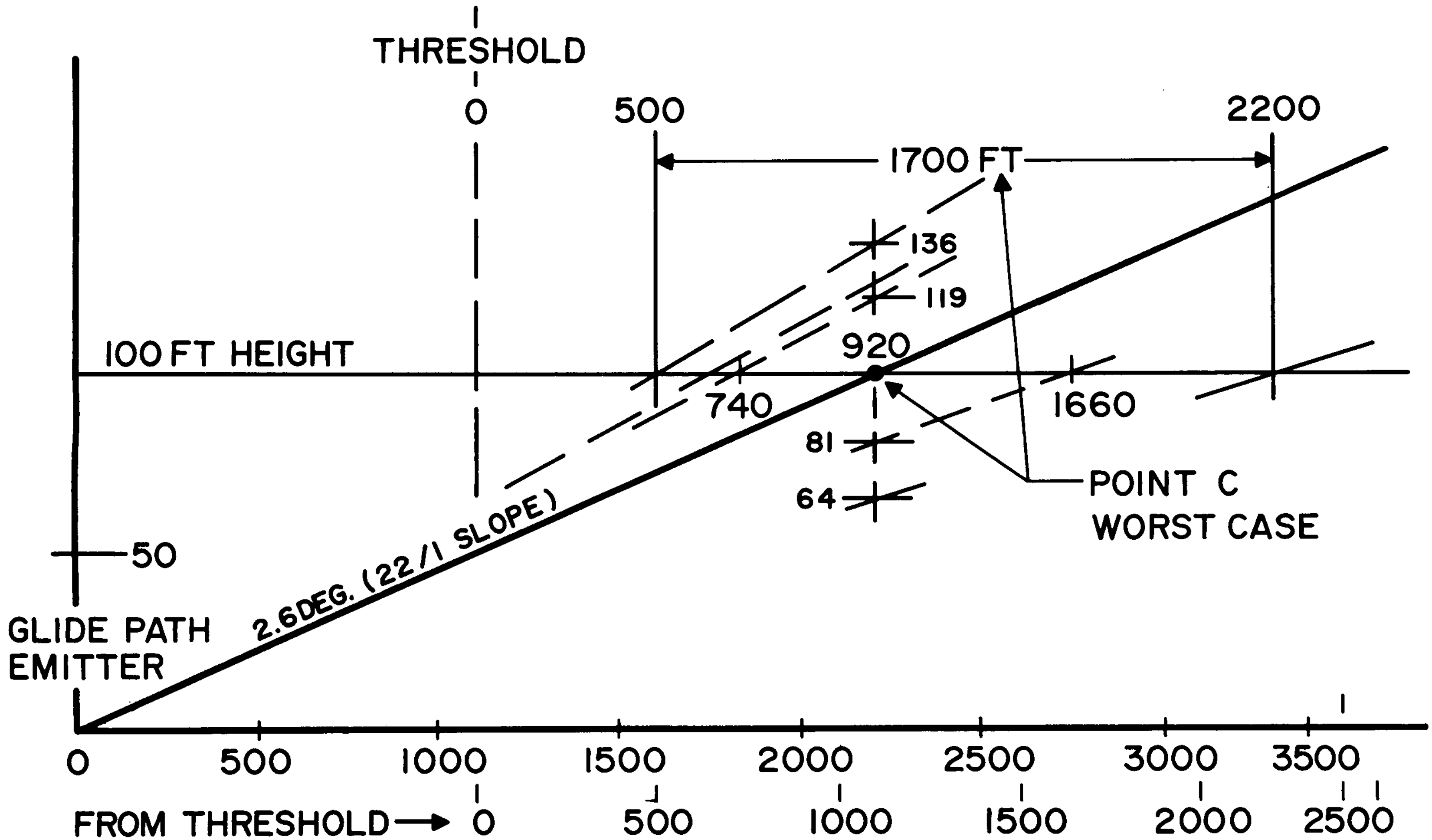


FIGURE 21

VARIATION IN POINT C (HEIGHT = 100 FEET)
WITH GLIDE SLOPE ERRORS

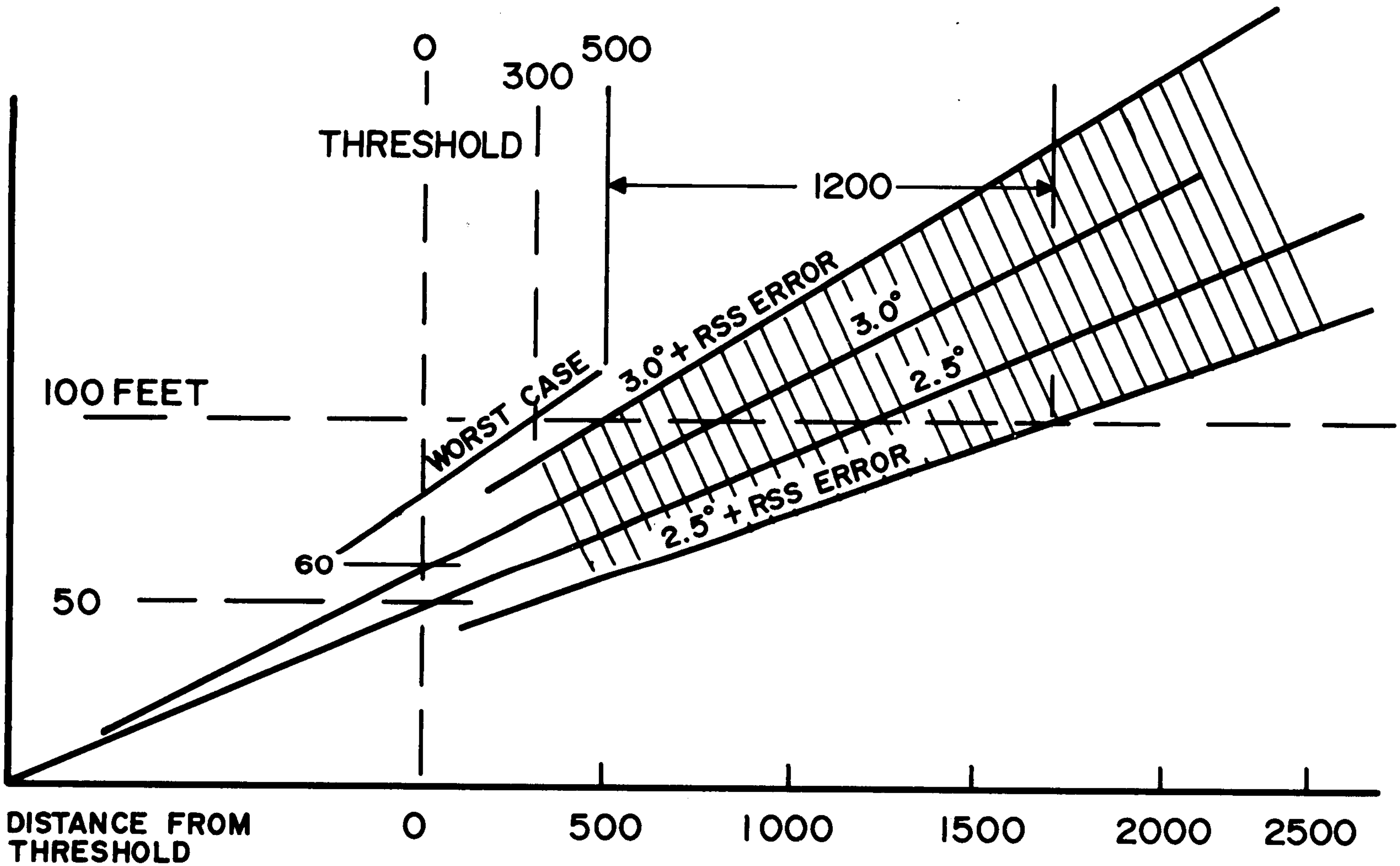


FIGURE 22

3 SIGMA RSS ERROR ADDED TO 2.5 AND 3.0 GLIDE PATHS
(NOTE VARIATION IN POINT C--100 FEET ON PATH)

This now causes the 3 sigma location of point C (not the worst-error case) to be located only 500 feet from the threshold on a 3-degree path (plus the angle attributable to other errors).

Figure 23 is a more critical examination of the ICAO glide path errors over the runway threshold (note the scale factor change). This creates a total vertical dispersion over the runway threshold of 36 feet (ICAO 10-foot path variation and 3 sigma errors). The worst case is considered quite possible this close because of the 4 to 1 linear "tightening" or convergence of the guidance signal from point B. The worst vertical dispersion can be about 60 feet (±30 feet), centered at a point about 55 feet above the threshold. It is interesting to note that in this worst case the path can be at about 1.2 degrees and the wheels (if 20 feet below the electrical path due to pitch rotation) at only 5 feet above threshold. They can also be as high as 60 feet. Although in measured VFR operations there is little correlation between visual flight and this path, it is a key point in ICAO consideration and much discussion ensues in the documentation relating to it.

The visual flight path as measured on several occasions is such that the wheels are about 20 feet high and follow a path about 1.8 degrees over threshold. There is a tendency on the pilot's part to lower threshold wheel heights and to flatten the flight path angles as the visibility deteriorates.

Considerable work is needed to resolve this dilemma, since in the worst case the wheels would be as much as 60 feet over threshold on a path angle of about 3.3 degrees. The significance of the dispersion of threshold height is that these same figures, with little modification, are being considered for CAT III-A as well as CAT II. These large variations in flight path have enormous effects on the visual cues the pilot receives in CAT II and CAT III-A. They appear to be markedly different from the usual, routine, visual cues. Figure 24 summarizes these

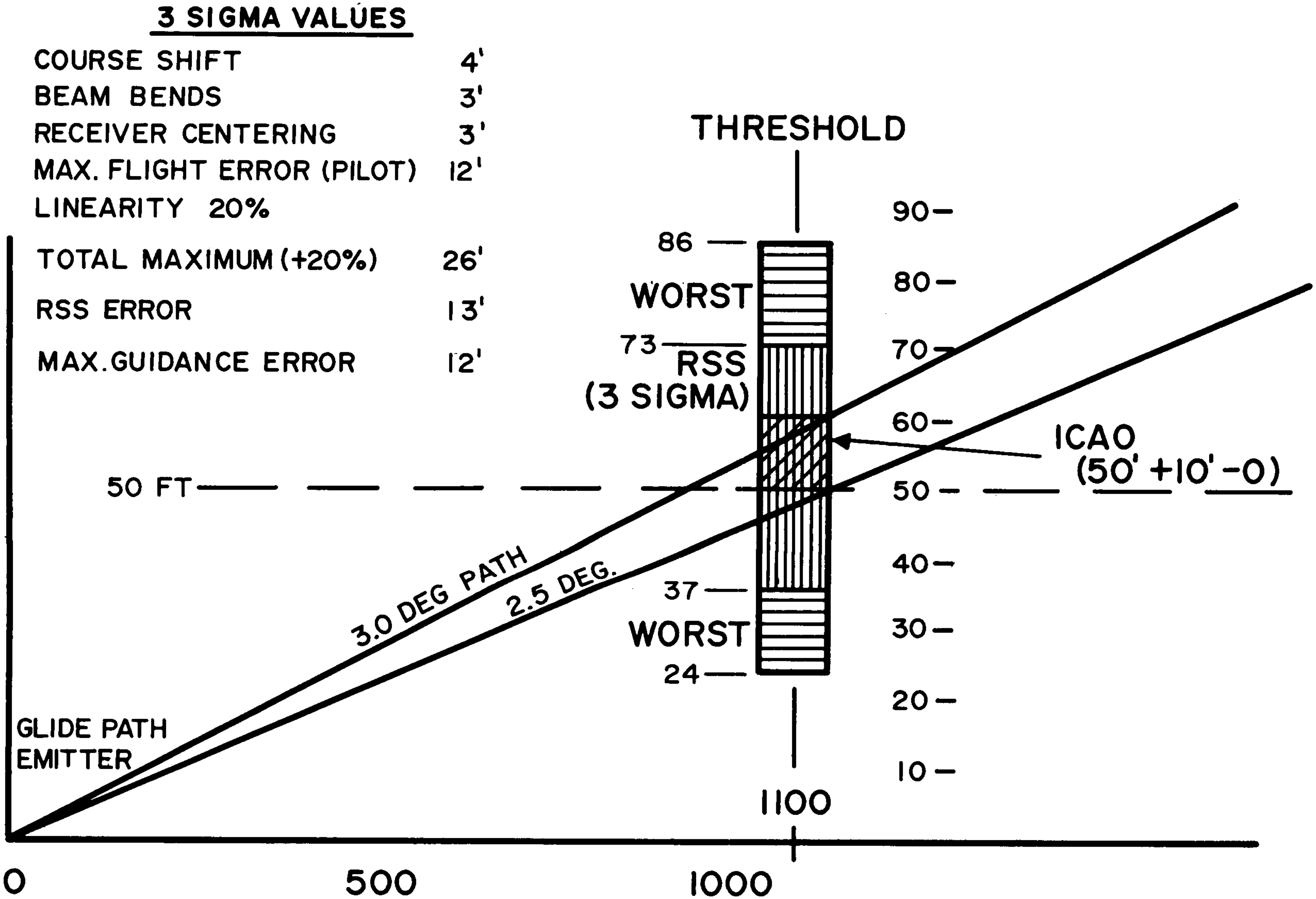


FIGURE 23

GLIDE PATH ERRORS OVER TYPICAL THRESHOLDS
ADDED TO ICAO VARIATION IN PATH HEIGHT

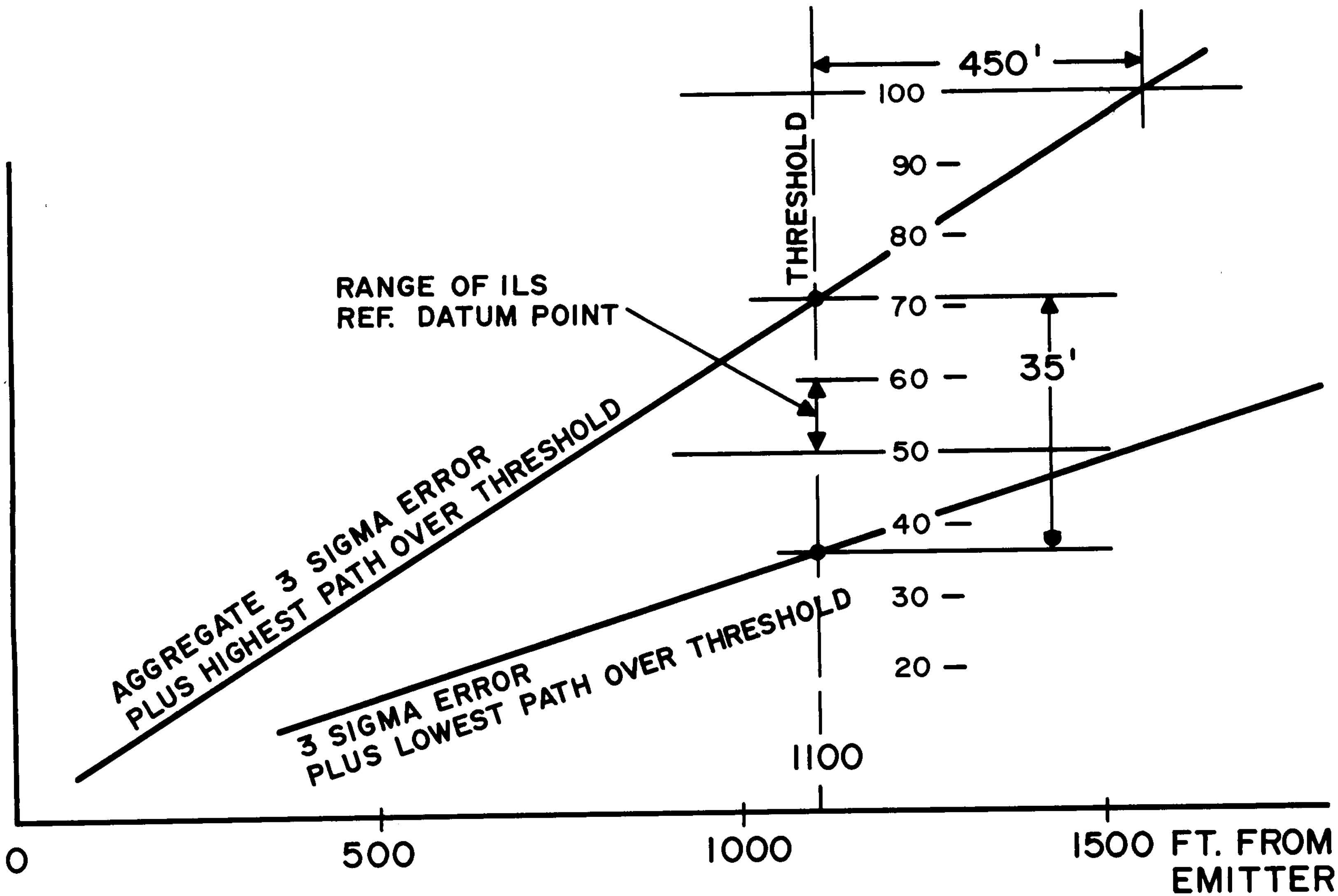


FIGURE 24

GLIDE PATH VARIATION OVER THRESHOLD
(PATH-ELECTRICAL)

variations, indicating that the 3 sigma (electrical) path can vary from about 36 feet to about 72 feet, or about two to one. Note also that the 100-foot height is as close as 450 feet from threshold.

Figure 25 describes the vertical path error curves out to ranges of 5000 feet and heights of 250 feet. It will be noted that the longitudinal dispersion at 200 feet is about 1750 feet and that the height dispersion at point B is 90 feet using these standards. Even for CAT I this raises questions of tolerances, since the dispersion places the pilot's eyes at around 4000 feet from threshold in one case and only about 2200 feet in the other case (each case being at a height of 200 feet). This 2 to 1 variation from one landing to another of the first visual contact is not conducive to pilot confidence, since the normal VFR visual flight dispersions are far less than this. In one case the pilot will see but 1400 feet of approach lights, while in the other case he will see the full 3000 feet of lights.

This is a related point to CAT II, since nearly all the factors leading to the design of the current approach light system were related to the "200 and ½ mile" concept of past years. The thought was that when the pilot broke out of the overcast and could see the surface he would have before him a long line of bright lights leading him to and over the threshold. Ample time for maneuvering to correct errors in vertical, horizontal, and longitudinal guidance were available along with excellent visual cues, vanishing points, etc. This caused a close correlation in flight paths to occur near the threshold for both IFR (200-½) and visual conditions. The pilot, in essence, flew by VFR criteria for some 5500 additional feet to touchdown after visual contact. The pilot has in CAT I just enough time (in even 3 sigma cases) to acquire the visual cues, assess them, and exercise judgment before actually reacting. He will have the aircraft aligned with the lights by the time threshold is reached. The aircraft can be fully aligned by normal VFR means,

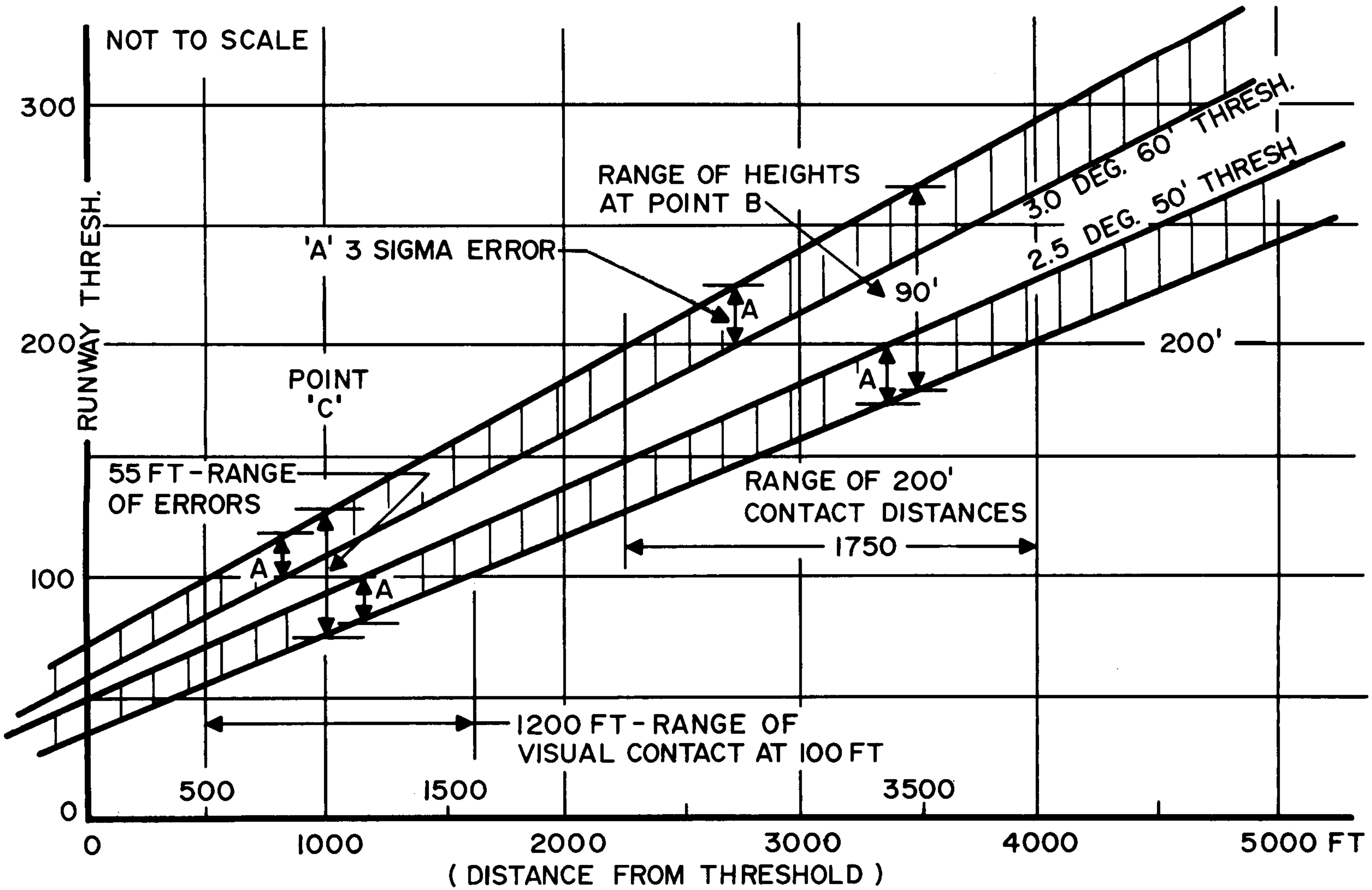


FIGURE 25

VARIATIONS IN HEIGHT AND DISTANCE FROM THRESHOLD FOR ICAO TOLERANCES IN GLIDE SLOPE INCLUDING AC 120-20 FLIGHT ERROR since the maneuvering times and distances are ample to achieve this in CAT I before arriving over the threshold.

The CAT II pilot will have nearly the same displacement errors (see Figures 15 and 16), but only half the time for the correction. In fact, if the errors place the pilot high on the glide path the time will be less than ⅓ that which he is accustomed to in the better CAT I cases (riding low on the glide path). The bank angle limits available for control upon obtaining visual ground contact at 200 feet can be much greater, so that the lateral side-step maneuver to align the aircraft with the lights is accomplished in much less time. The lateral errors are only slightly less in CAT II, but bank angle limits may be limited to ½ to ⅓ of CAT I limits. The pilot at a 100-foot decision height will not roll the aircraft the same amount or at the same rate. When he descends lower than 100 feet he will consequently be even further limited when the time arrives to execute a corrective roll to reduce a lateral error and introduce an ample intercept angle essential to returning to centerline. Thus, the bank limits, if reduced to about half the amount, would require nearly twice the distance for the equivalent side-step maneuver. The time can be shortened for the visual period to about ⅓, and the maneuvering period can increase by nearly two times; a factor of as much as 6 existing between CAT I and CAT II. These are highly incompatible situations for accomplishing a high ratio of successful approaches and landing in CAT II. It is argued by many that the number of missed approaches for reasons of inadequate guidance or piloting must be reduced for CAT II over the CAT I rate of missed approaches, since the risk factor has increased many times. Some estimate an increased risk of 100 times. W/P 142 (IATA), which was previously referenced, has made this estimate. With London data indicating that the number of missed approaches increases to nearly 50% in CAT II (from about half this number in CAT I), the trend is in the wrong direction and is intolerable.

1. COMBINED ERRORS OF LATERAL AND VERTICAL GUIDANCE

Figure 26 combines much of the foregoing information into a composite perspective to illustrate the effect of a "window" at point B portraying the vertical and horizontal (guidance and flight) tolerances at this point. The full-scale regions and the 3 sigma error contours are illustrated. It should be recalled that, though the runway is 150 feet wide, its useful width is considerably less. In this report it is suggested to be 90 feet wide, but some suggest a width of 60 feet. Thus, a lateral window dimension of 280 feet would suggest that from this point a side-step maneuver of 110 feet may be encountered and that the pilot's eye height may vary by about 20% from the nominal height. Point B it will be recalled is defined in range from the threshold, not in altitude as is point C. A "vertical window" describes this best.

Point C is shown in Figure 27 by assuming a "vertical window" centered on a nominal path angle and a height of 100 feet for its location. The vertical dispersion is now nearly half the previous value, and the lateral dispersion is 235 feet. Note that the vertical dispersion has decreased more from point B to C than is the case for lateral dispersion. This is due to the proximity of point C to the vertical guidance transmitter (angular origin) and the relatively small change of distance to the remote lateral guidance angular origin.

Consequently, the side-step maneuver is now reduced to about 90 feet under the same assumptions of the point B discussion. This reduces the side-step maneuver by about 20%. As noted, however, the time may be reduced to ⅓ that at point B and the bank limits may be such as to require twice the longitudinal maneuvering distance to achieve this amount of side-step with severely limited bank angles that plague the pilot (or

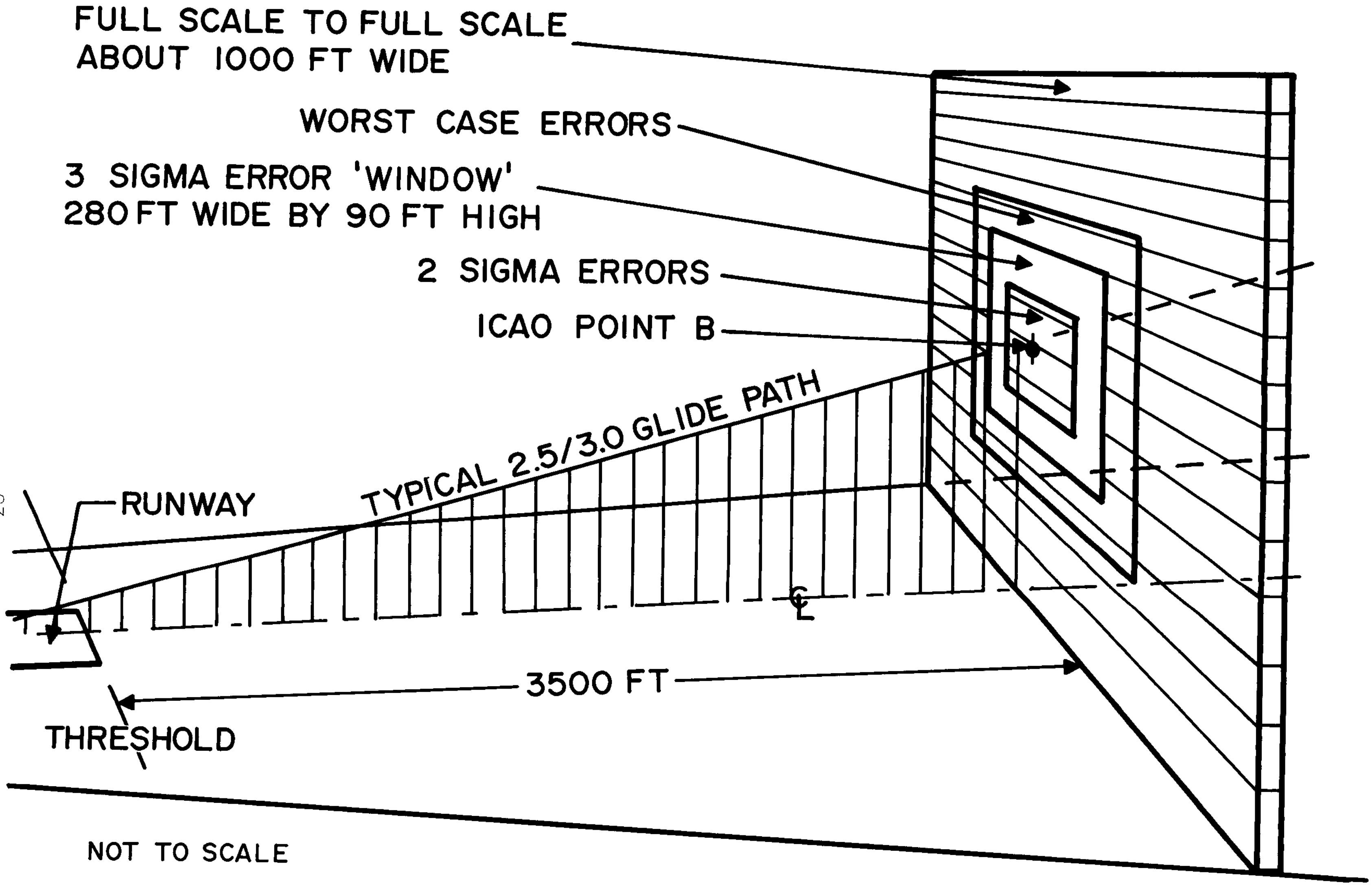


FIGURE 26

ICAO/ILS POINT B TOLERANCES
(VERTICAL WINDOW CONCEPT)

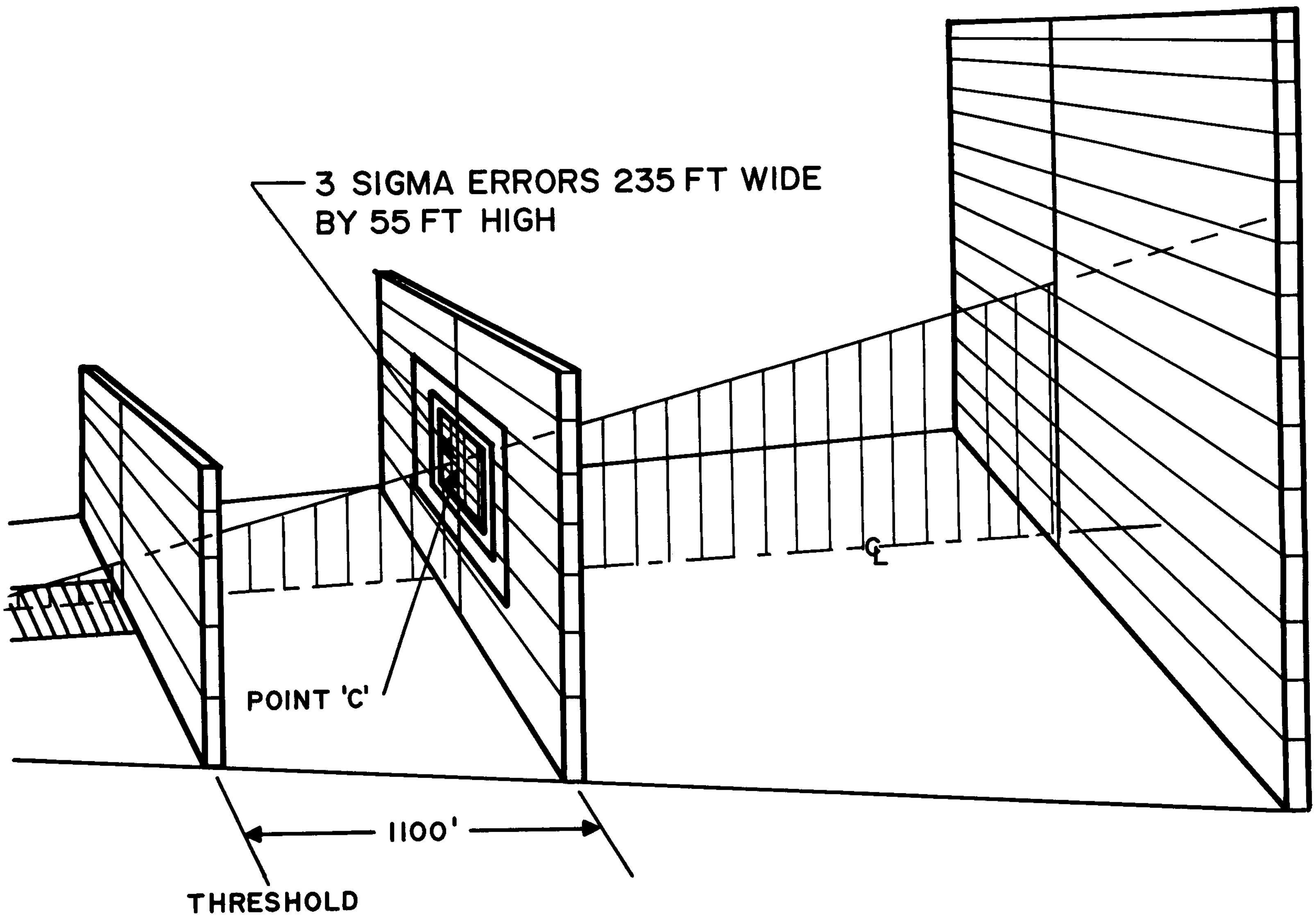


FIGURE 27

COMBINED ERRORS AT POINT C (100-FOOT HEIGHT) autopilot) at such low heights. This severely limits the pilot's ability to complete a successful landing.

The combination of both the side-step maneuver and the vertical correction maneuver (often referred to as the "duck-under" maneuver) should be examined by simulation. In the latter case, the pilot often increases sink rate to correct for the excessive heights that he encounters when the errors are on the high side. Simulation of one error at a time would be beneficial while including increasing amounts of the other error. It is not likely that as much bias (skewness) in lateral error will appear in the data as in vertical errors. Photo measurements of operational aircraft landings under operational conditions suggest that the errors will not be a normal distribution as viewed by the pilot at point C. It is probable that, based on previous data, the tendency will be to fly low on the path well beyond the stipulated amount to obtain visual contact (at a given ceiling) further from the threshold for a specific height, adding time to correct lateral errors.

Another instructive example is the creation of a "horizontal window" at the 100-foot height. This window concept includes all the possible 3 sigma positions the pilot may be at, as he views the surface from an approach height of 100 feet. They include the lateral and longitudinal dispersion of errors and typical path variations. It should be noted that no single path at a specific runway would have this specific size window. However, the "total system" errors involving several instrument runways can readily include this amount of dispersion. Since there are around 500 ILS installations (sometimes four per airport) in the world today, many combinations can exist. This number is used to illustrate the quantity of 3 sigma errors that may be encountered.

The purpose of the 1200-foot x 235-foot horizontal window (Figure 28--containing all possible locations of point C)

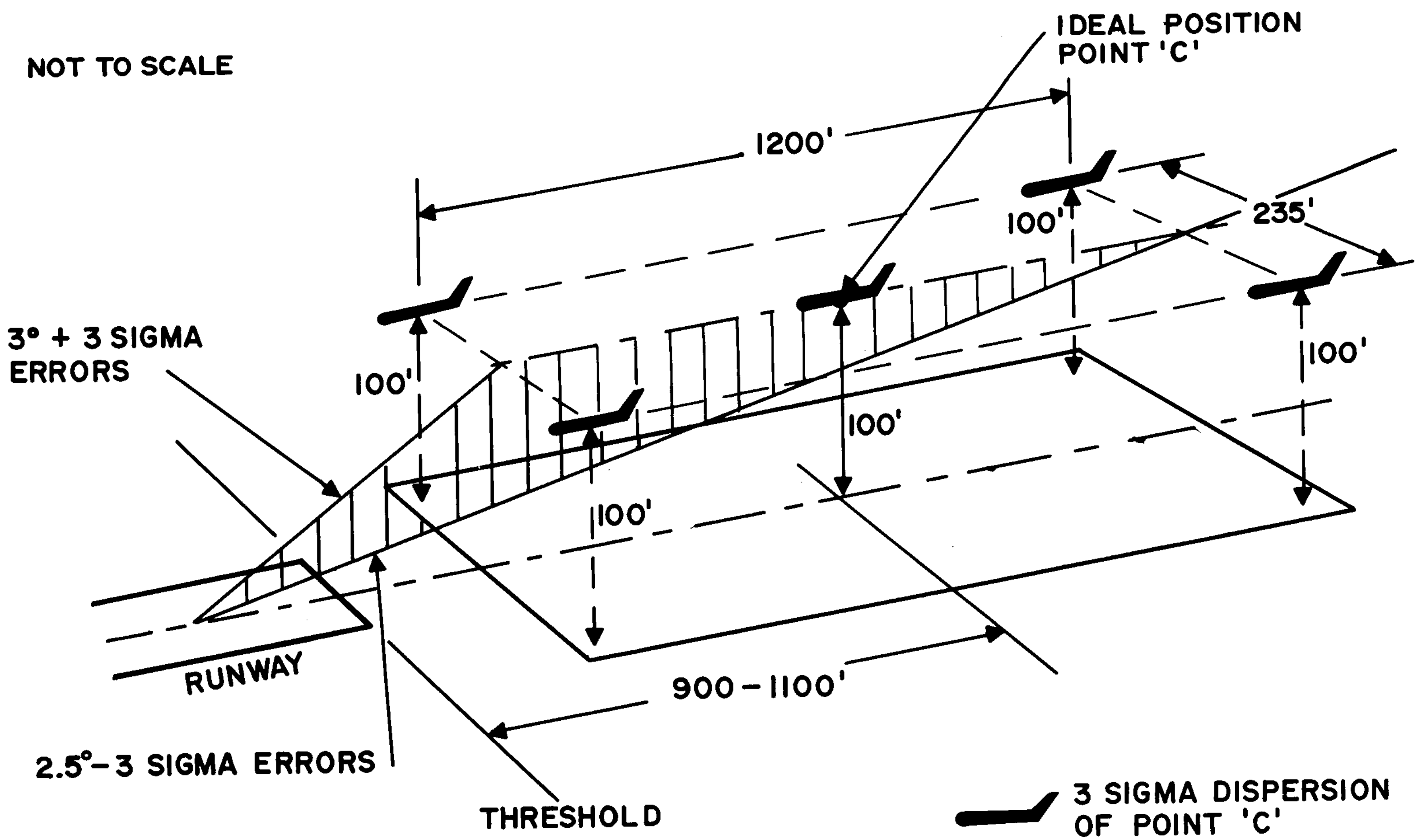


FIGURE 28

LONGITUDINAL AND LATERAL DIMENSIONS OF 3 SIGMA 100-FOOT WINDOW
(ALL POINTS IN THE AREA ARE AT A HEIGHT OF 100 FEET)

is to illustrate the wide range of viewing positions and the fact that the vertical errors above an ideal course create less horizontal dispersion toward the threshold than equivalent glide path errors below the path. In addition to the wide variation in the position of the CAT II decision height, there may be other diversionary cues that occur simultaneously--for example, excessive cross-track velocity, undetected crab angle, or other attitude variations that add to the problems of recognizing (within a few seconds) what relationship the aircraft has with respect to the limited ground references. The large longitudinal dimension (1200 feet) is due to the variations permitted in the shallow angles of the glide path.

Figure 29 is similar, but the 100-foot "horizontal window" dimensions have been projected downward to the elevation of the runway threshold. This might be considered a "footprint" of the total 3 sigma variations that may be encountered in the aircraft's position. Note that the nearest point for viewing the runway from a 100-foot height is 500 feet from the threshold and the most distant point to view the runway from a 100-foot height is about 1700 feet from the runway. This is a variation of about 3 to 1 for point C relative to threshold. These dispersions change the expected image size of the runway threshold (angle subtended by runway width) by 3 to 1. There are similar major changes in the vertical perspective. When examining Heads-Up displays using runway images, aiming points, etc., this fact should be borne in mind. The pilot will have some hints as to which direction he may be in error (experience at a specific runway, his small CDI indication, etc.); yet, the full realization will not come until he has acquired and recognized some of the visual cues from the ground, utilizing what he can see with but 1200-foot visual ranges from ILS point C.

It will be seen in Figure 30 that at a slant range of 1200 feet to the ground and with a cockpit cut-off angle of about

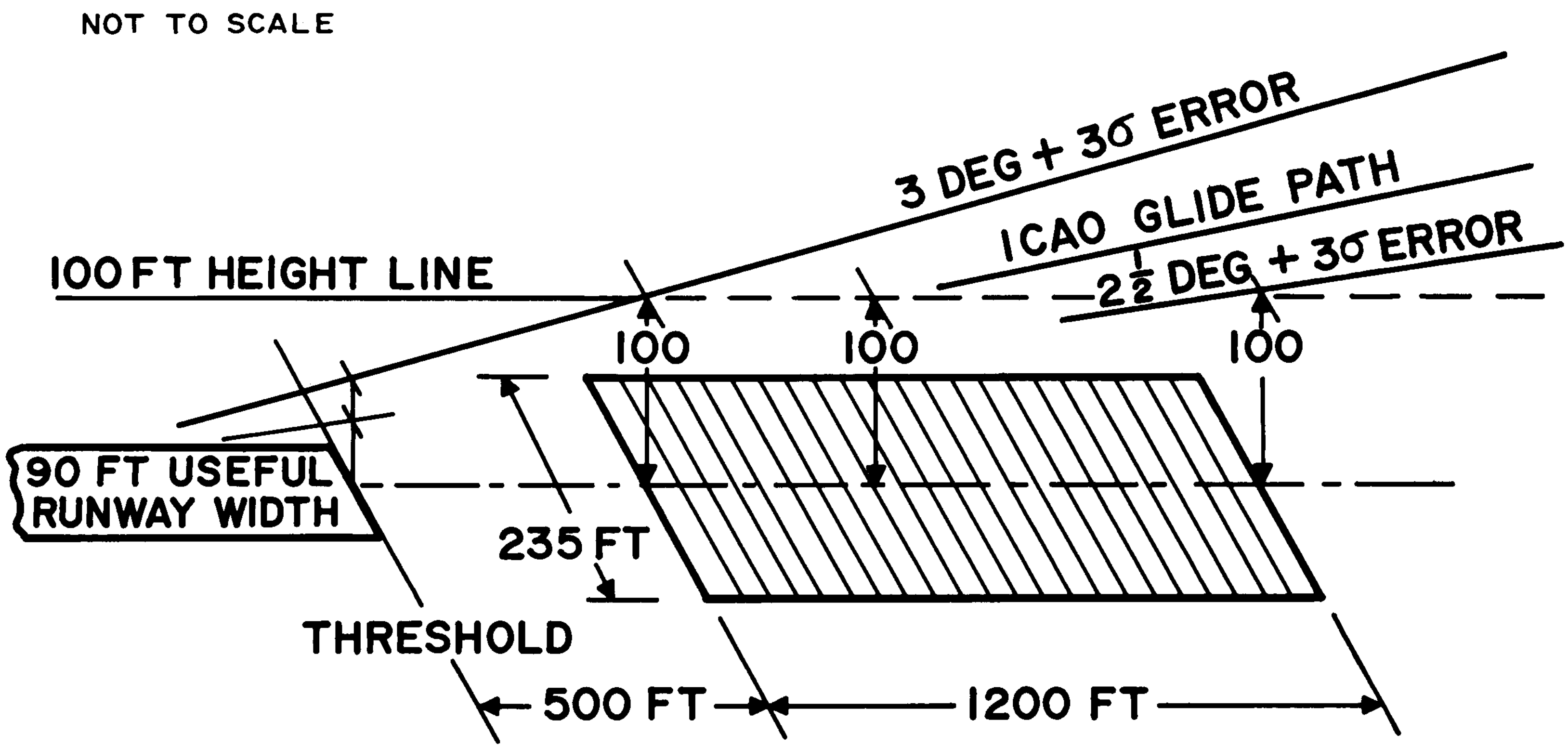


FIGURE 29

ICAO GLIDE PATH AND FLIGHT ERRORS COMBINED WITH LOCALIZER ERRORS
AT ALL 100-FOOT HEIGHTS AND PROJECTED TO THRESHOLD ELEVATION

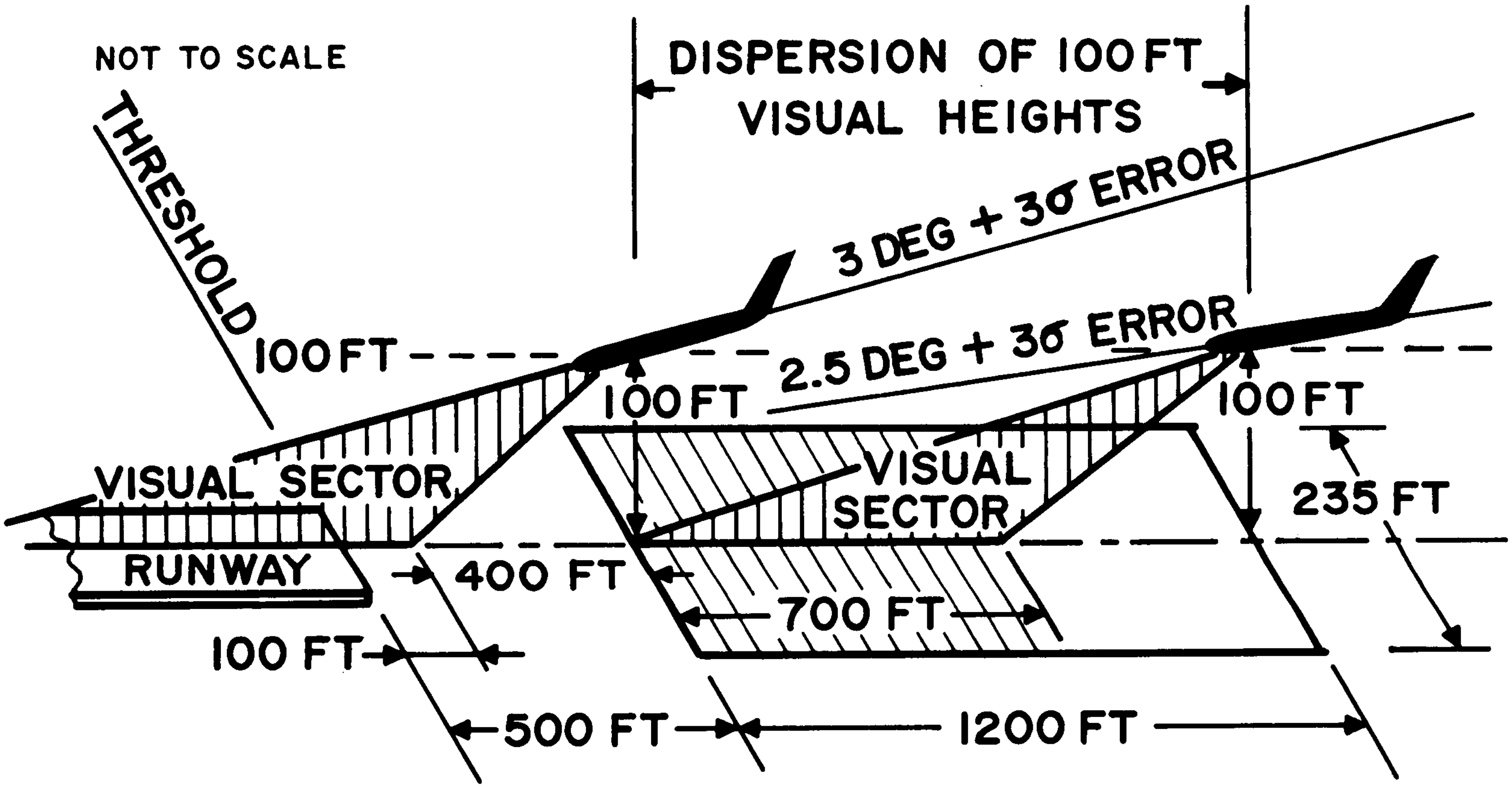


FIGURE 30

ICAO VARIATION IN VIEW OF SURFACE FROM 100 FEET
CAUSED BY GLIDE PATH DISPERSIONS WITH 1200-FOOT
(SLANT) RVR AND A COCKPIT CUTOFF OF ABOUT 14 DEGREES

14 degrees, only about 700 feet of the surface will be visible; the more distant points, of course, vanish at the limit of RVR (slant). The RVR is not always equivalent to slant range, and in some parts of the world the two can have wide variations because of the laminar or non-laminar nature of the fog or other visibility restricting media. In the case of the aircraft nearest the threshold, only about 100 feet of approach lights are available, whereas in the other limiting case some 700 feet are available, and they continue to be available for about 6 seconds vs ½ second. This is a 12 to 1 ratio of times available to make a most critical judgment. Nominal speeds of 200 fps are assumed in this region.

If the pilot is to remove the aircraft's lateral and longitudinal error some maneuvering time is needed. These figures portray several aspects of the 100-foot visual height problem in correcting the errors that will exist in many cases. Depending upon how the signals (error directions) combine, the pilot may have a CDI deflection, say to fly left, by a readable amount and can be prepared to do so at the time of adequate visual contact and find himself actually on centerline. Again the concern exists that the path deviation indication does not agree with the actual world in a region so sensitive to visual cues.

Figure 30 illustrates the point of the visual sector that the pilot will view, assuming that the slant range visibility is also 1200 feet at the limits of the CAT II operation. The pilot does not see his "aiming point." This is defined as the point on the surface that the flight path of the aircraft, continued in the same direction, would finally contact. Even if the pilot is flying the ILS glide slope precisely, thus establishing such a point and path quite accurately, he will not see the ILS aiming point, since it is obscured from vision around 1000 feet from threshold.

The ability to judge the aircraft's aiming point may be far more significant psychologically than anticipated. Without it the pilot is forced to mentally integrate over the short visual surface segment. He flies by observing it for a given period and integrating from one visual segment to the next, thus determining from this misleading, depressed viewing angle the actual vertical flight path angle of the aircraft.

The lateral errors and corrections are far more obvious, but not the vertical errors (or corrections thereto). As shown in Figure 31, the most distant object visible is about 1200 feet in front of the aircraft depressed at an angle of about 4.5 degrees at a 100-foot height and about 7 degrees at a 150-foot height, the height most likely for first visual contact. By ICAO definition, the 100-foot decision height is the point at which pull-up is initiated if the landing is abandoned because adequate visual contact had not been previously observed for a sufficient time to continue the landing visually under CAT II concepts. It is likely that since the angle for CAT II never decreases below 4.5 degrees (changing slowly from about 7.0 to 4.5, increasing with descending height, sufficient vanishing point cues will not exist. These are recognized cues that aid in judging vertical height, sink rate, and path angle. Furthermore, the center of the visual segment is depressed in angle even more, being 7 degrees at 100 feet and 9.5 degrees at 150 feet. These are depressed surface segments somehow requiring reference in the pilot's mind to an intended landing point on the runway. These depressed segments cannot be seen at the time of decision nor during judgment periods. Not being able to associate these angularly depressed cues with normal visual flight cues, the pilot may not be able to estimate where he is in height or the aiming point.

Although no data on this seems to exist, the generation of such information is critical. The pilot probably looks out the windshield in a normal VFR landing using some cues at least

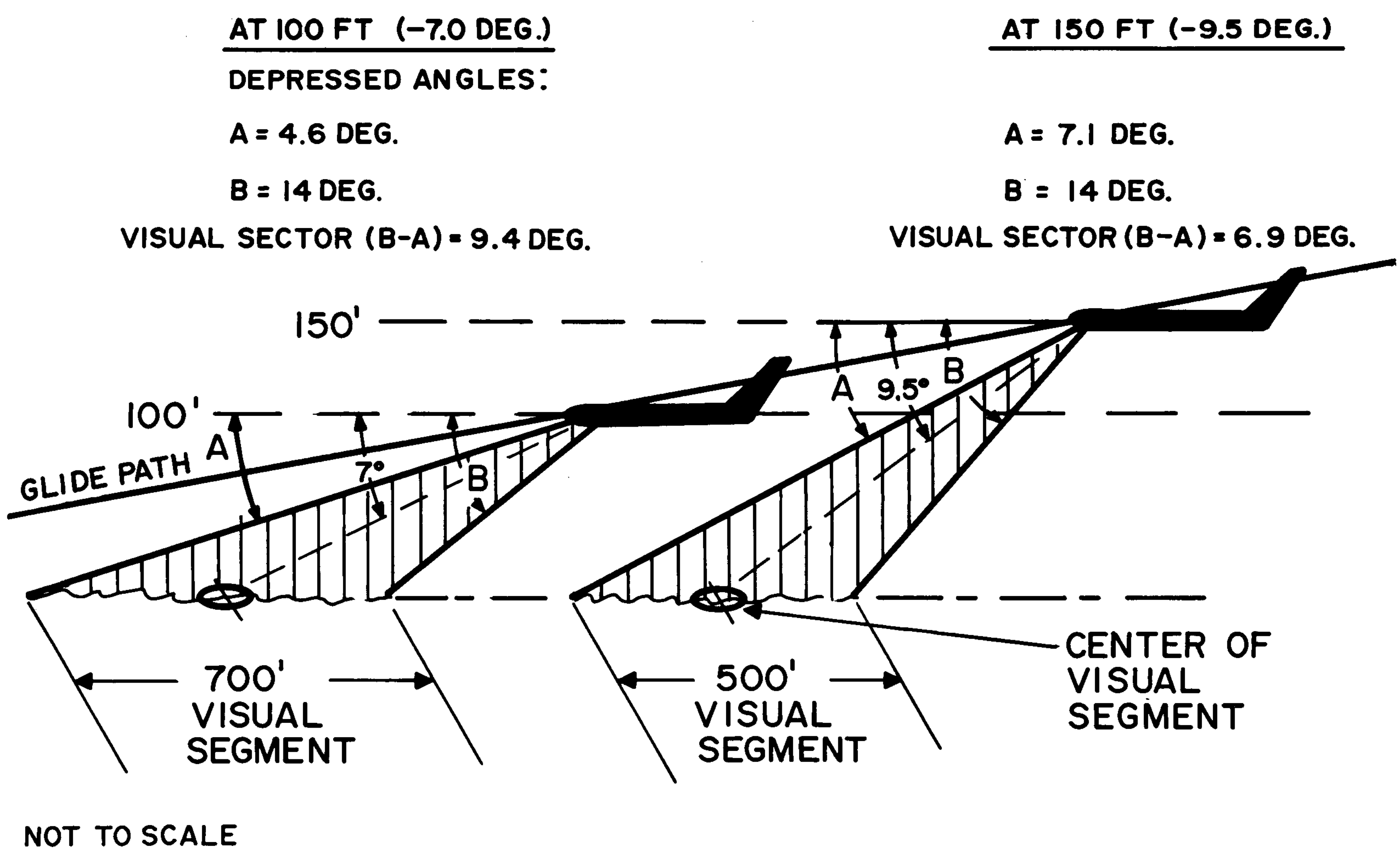


FIGURE 31

ANGLE BELOW THE HORIZON TO CENTER OF VISUAL SEGMENT
FOR HEIGHTS OF 100 AND 150 FEET IN CAT II OPERATION

2000 to 3000 feet ahead of the moving aircraft. Although little is understood about the visual psychological cues needed to drive an automobile, the Department of Health, Education, and Welfare has opened (in early 1967) a research center to attempt to determine important driver cues. In the auto, the driver's eyes are at a constant height; this is not true with pilots. Thus, this test of depressed short visual segments is suggested, since it is known that small (½ degree) runway slopes beyond the threshold are detrimental to good landing performance (dispersion and sink rate). Furthermore, Navy pilots landing aboard carrier decks seem to utilize visual points about this far away. Viewing roughly along the flight path of the aircraft seems instinctive and is denied by forcing surface viewing angles depressed by 2½ to 3½ times normal glide path angle. A test should be conducted in which the cockpit cutoff of around 14 degrees is supplemented with another cutoff at about 7 degrees because of RVR limits. An examination should then be made of what the pilot does with the remaining 7-degree wide sector. At a 150-foot height (Figure 31) the visual segment is less than 500 feet in length.

2. PITCH REFERENCE

In addition to difficulty in establishing the vertical flight path of the aircraft as he looks out the windshield, the pilot has an additional problem. No horizon that is representative of pitch attitude is available. The roll horizon may be available if the surface lights are correctly used and seen by the pilot, but this is not true with the visual pitch cues. Thus, not only will the pilot have difficulty in visually determining the aiming point of the aircraft but he will also have increased difficulty in attempting to correct it with pitch changes, because no references exist for pitch with a 500 to 700 foot surface segment (at about -7 degrees) for the correction. This may argue for a "heads-up display," but not necessarily so since the registry of the aiming point, lateral error, longitudinal errors, and rates of error change must be near perfect or they will so distract the pilot that he cannot establish the true pitch attitude from viewing outside the aircraft under the CAT II criteria.

Figure 31 shows that a total vertical surface segment, only 7 to 9 degrees in width and with centers depressed from 7 to 9.5 degrees below the actual horizon, exists at 1200-foot visual ranges. The pilot viewing this may get the illusion of a changing pitch attitude or pitch reference, since the surface segment becomes longer and the angle to its center is moving upward gradually. This may give an illusion of a pitch change that has not in reality occurred, or, at least, confuse any existing pitch cues.

Similarly, the length of the visual surface segment increases from only 600 feet to over 1000 feet as the height of the aircraft is decreased. This visual complexity is illustrated in Figure 32. Note that, in addition to this change of length, the center angle viewed from the cockpit changes by about 2 to 1; yet even at threshold height, does not arrive at the flight path angle of the aircraft. The enclosed angle of the total visual sector changes about the same amount (2 to 1). The obviously better visual cues at the lower heights are an aid to the pilot. The problem is: How does he safely arrive in a situation to see them? Upon seeing them, so little time is left to do anything except to hopefully observe a good landing. Figure 32 illustrates the path of the measured visual flight paths showing that the viewing angle over threshold because of a lower threshold height finally encompasses the flight path of the aircraft and its aiming point so that it is near the center of the visual segment. This may be a highly significant reason explaining why pilots "duck-under" in low visibility. Also note that the visual segments are located further from threshold in the latter cases, giving the pilot more time to

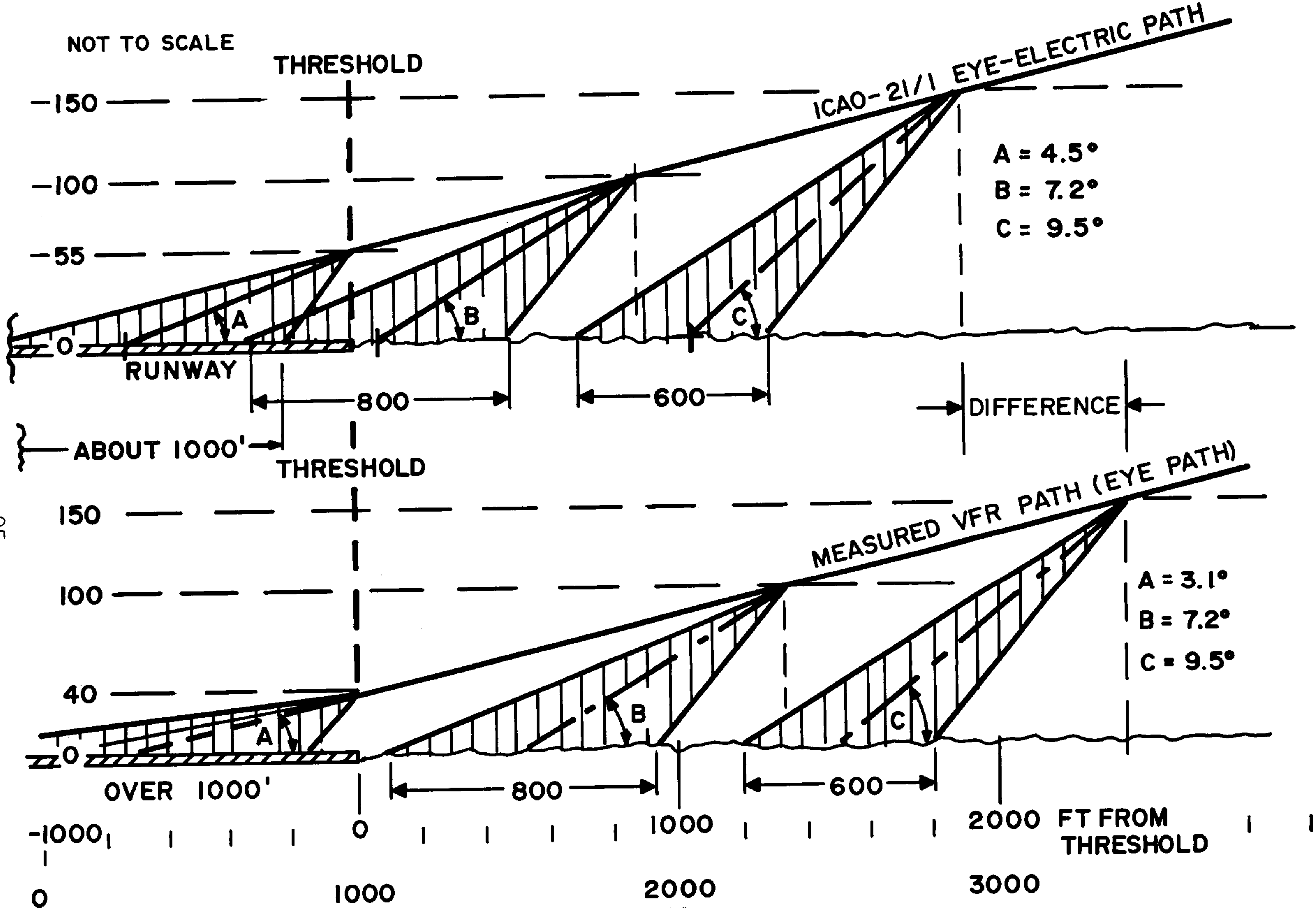


FIGURE 32

COMPARISON OF ICAO AND VISUAL FLIGHT PATHS AT 100 FEET, AND THRESHOLD UNDER CONDITIONS OF CAT II LIMITS (1200 RVR AND SVR) utilize what he sees at a specific height. This additional 2 seconds may also be significant.

These ideas are summarized in Figure 33, which illustrates these sensitive vertical angles at specific points on the landing path. Note that for an eye level (height) change of 7 to 1, the vertical angle (negative) to the most distant visual point changes by 14 to 1 and arrives within ½ degree of the horizon. The total subtended angle of the visual segment varies only 2 to 1 as does the actual length of the visual segment. The complex relationship of these critical vertical angles, the pilot's ability to integrate negative (depressed) angles up to -9 or -10 degrees, and the motion of the moving, short, surface segment all need considerable visual and pilot research using new, realistic simulators designed solely for this effort. These values of Figure 33 are tabulated below. Figure 34 illustrates this for CAT III-A.

ICAO CAT II Significance	Eye Level Height (feet) above Threshold	Vertical Angle to Most Distant Surface point	Total Subtended Angle to Visual Surface Segment	Length of Visual Surface Segment (feet)
First Visual Cue	150	(-)7.1°	6.9°	about 585
Lowest Decision Height	100	(-)4.8°	9.2°	about 800
Threshold Height	55	(-)2.7°	11.3°	about 980
Roll-out	20	(-)0.5°	13.5°	about 1120

Figure 35 provides an index by which some crude estimates can be made of what the pilot will see in each position within the 100-foot "horizontal window." The total 3 sigma area at a 100-foot height is divided into blocks. They are identified by the letters A-F laterally and numbers 1-11 longitudinally. Block B-2 is shaded to illustrate the scheme (Figures 38 and 39

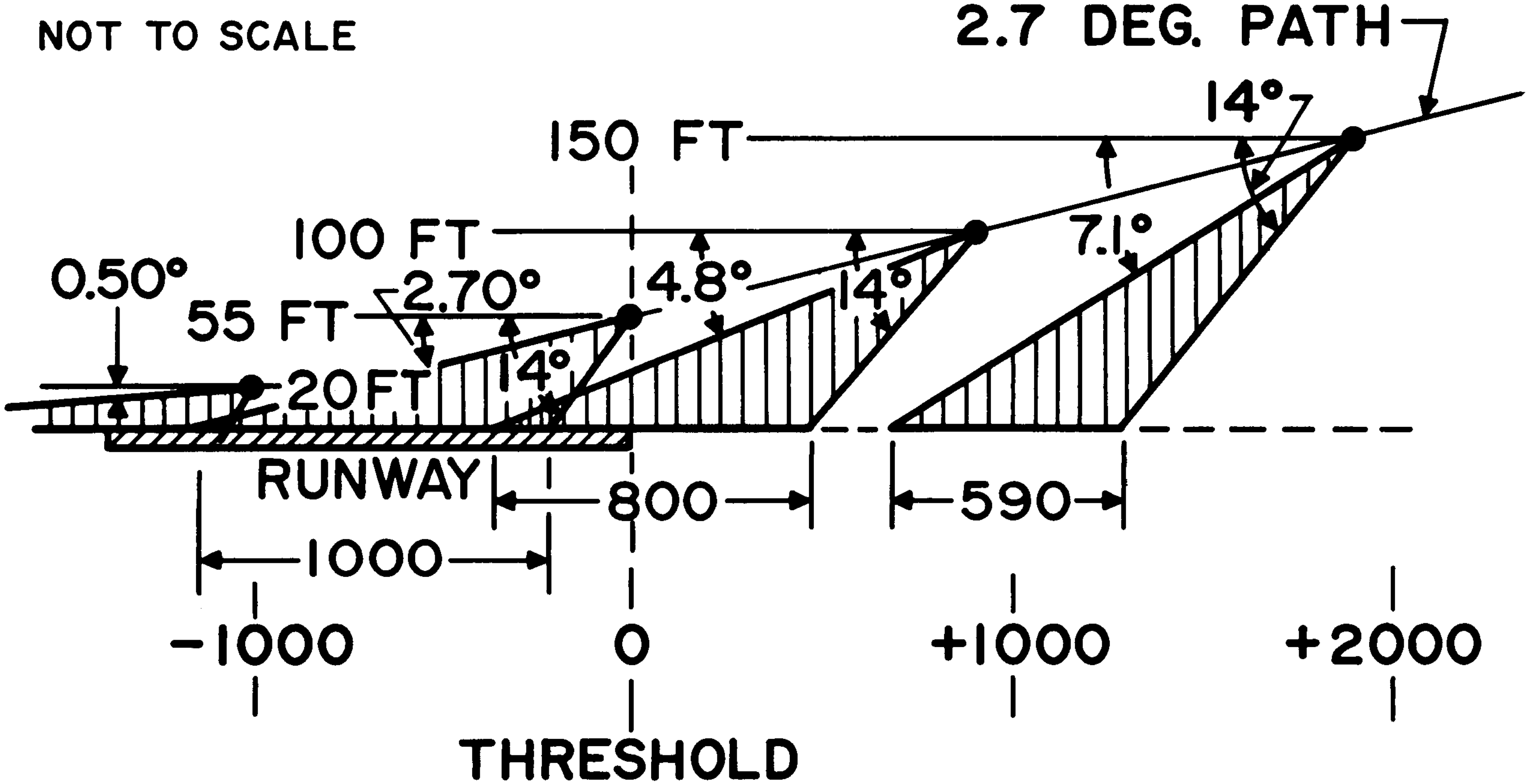
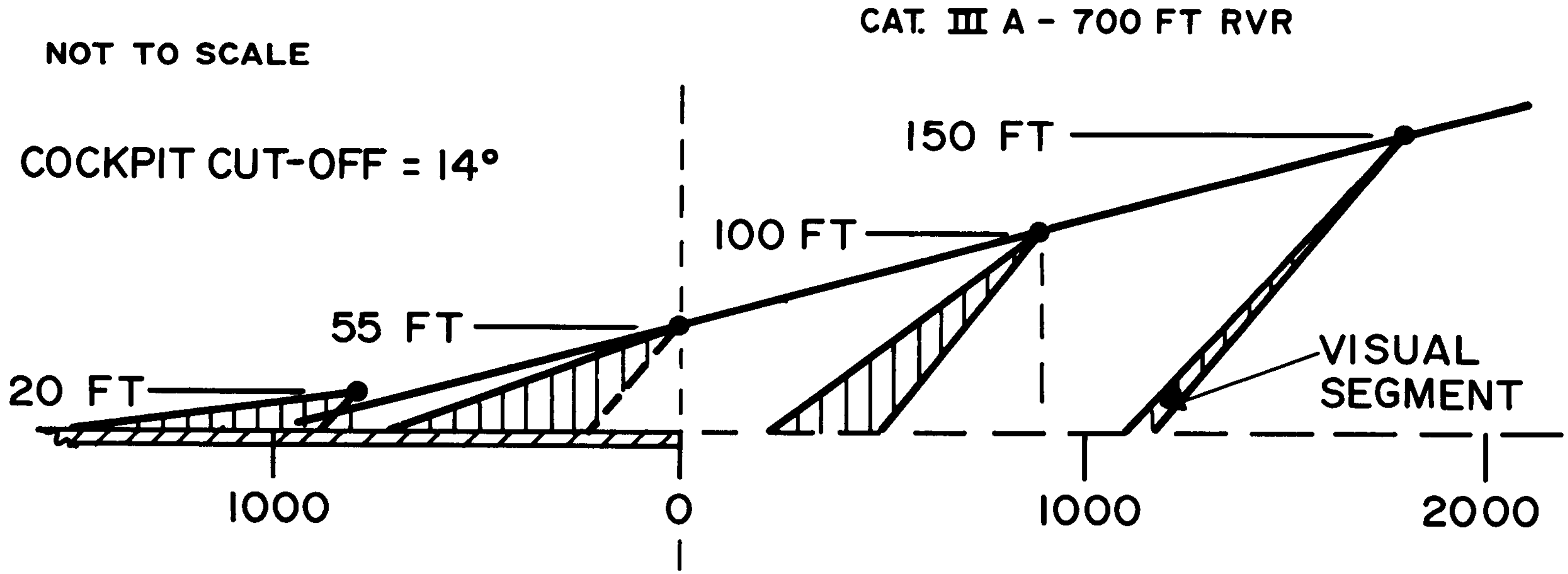


FIGURE 33

SIGNIFICANCE OF RVR AND SVR OF 1200 FEET
AND A DECISION HEIGHT OF 100 FEET



LOCATION (eye level) feet	Vertical Angle To Most Distant Point	Length of Visual Surface Segment (ft.)	Total subtended Angle to visual Surface Segment	Angle to Center of Visual Segment
150	(-) 12.1°	100	2°	(-) 13°
100	(-) 8.1°	300	6°	(-) 11°
55 (threshold)	(-) 4.4°	480	10°	(-) 9°
20	(-) 1.6°	620	12°	(-) 8°

FIGURE 34

EXAMPLE OF VISUAL RANGE OF 700 FEET AT VARIOUS CRITICAL HEIGHTS (NOTE THE OVER 7 TO 1 CHANGE IN VERTICAL ANGLE TO MOST DISTANT POINT AND THE OVER 6 TO 1 CHANGE IN THE VISUAL SEGMENT)

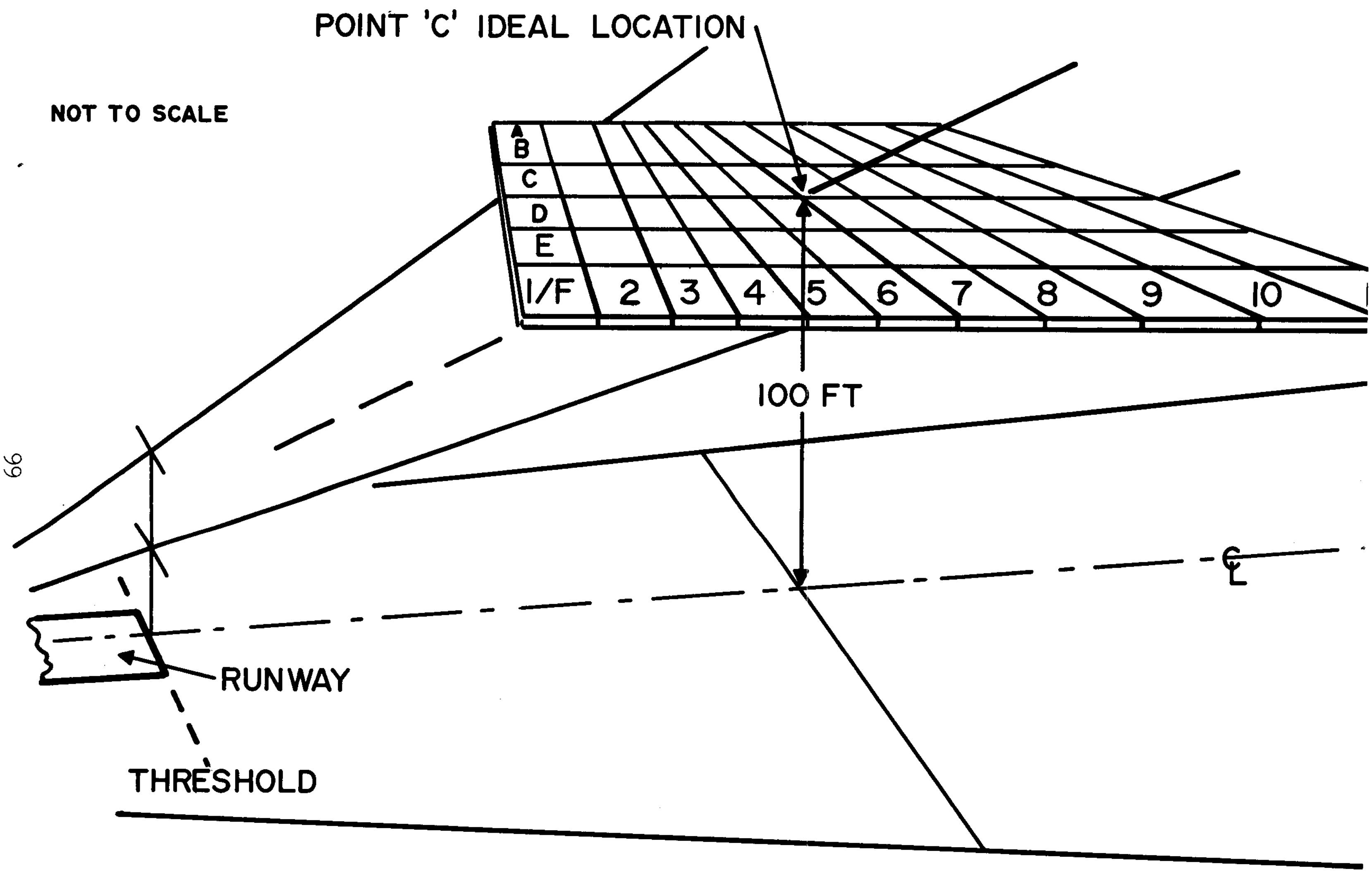


FIGURE 35

INDEX OF VIEWING POSITIONS FROM HEIGHT OF 100 FEET
(SEE FIGURES 28 THROUGH 34 FOR DETAILED DIMENSIONS)

are each identified accordingly). Each block is approximately 40 feet wide x 100 feet long. The vertical angles establishing "Row-11" blocks are less than the vertical angles establishing "Row-1" blocks. This is an obvious geometrical situation that results in a skewness in dispersion of possible block location not treated with normal distribution techniques. This is a means of moving ICAO-ILS point C around to positions relative to the runway threshold that are representative of the entire range of errors up to the 3 sigma values. As noted before, this example may or may not be representative, since several potential errors have not been accounted for in this analysis.

Furthermore, the normal distribution may not be representative of the various situations that may exist at specific runways. For instance, it is planned to use the radio altimeter for height measurements of point C. The time and position of the aircraft reaching the 100-foot point (or some previous point such as 150 feet) requires a specific vertical angle. DME is not always available, nor is its accuracy adequate. The ILS is only an angular system. Thus, most airlines have added the radio altimeter for this function in accordance with AC 120-20. However, terrain irregularities result in incorrect measurement of the height relative to touchdown elevation. Since this is the approved method of determining point C, it can be seen that additional scatter of this point can occur.

Figure 36 stresses this point. Even if a profile correction chart is used (as now published in some flight manuals) that gives the terrain-corrected height, it can still vary since the variation in the shallow vertical path angles results in large longitudinal dispersions. Thus, in this case, an actual profile on an instrument runway approach terrain (the 3 sigma error previously noted) will be exceeded. There is a general increase in irregular threshold profiles, since most jet runways are extensions of previous runways using land fill. Seattle, Washington, Pittsburgh, and LaGuardia, New York, are good examples.

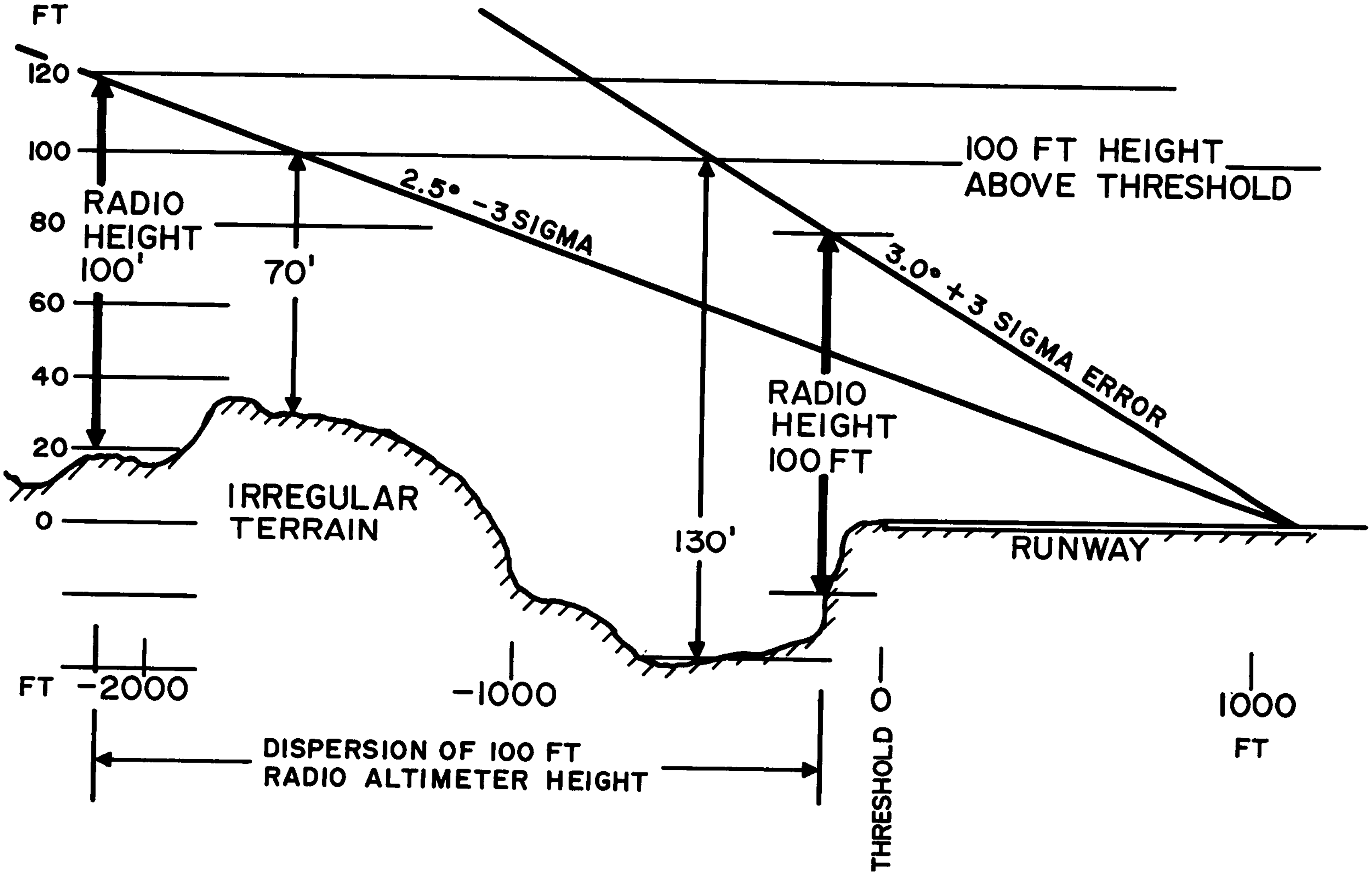


FIGURE 36

DISPERSION OF RADIO ALTIMETER HEIGHT MEASURE OF 100 FEET WITH VARIATIONS IN PATH ANGLE, RSS ERRORS, AND APPROACH TERRAIN

Figure 37 illustrates the approximate view the pilot would receive at a height of 100 feet if he were in position blocks 7-C, 7-D, 7-A, and 7-F. These are at a constant distance from threshold, nearly ideal for representing the nominal distance of point C. They demonstrate the effect of lateral errors. Both the 1 sigma errors (7-C and 7-D) and the 3 sigma errors (7-A and 7-F) are illustrated. The obscured, distant part of the runway (such as the vanishing point) is noted. This assumes a slant visual range (SVR) of about 1800 feet to obtain a view of the runway threshold from this position.

It should be noted that from these four positions (each representative of point C), the runway threshold cannot be seen with a visible range of less than 1200 feet. The pilot must rely on the lights with lesser RVR conditions (such as for CAT III-A) at this point until the threshold comes into view. Another problem is that the width of the runway (the subtended angle as seen by the pilot) is a very critical aspect of the maneuver. The visual cues suggesting how much side-step to make are probably closely related to seeing parts of the runway to judge the extent of available space and time to conduct the maneuver or whether to attempt it at all. All block rows beyond F in Figure 35 are positions of point C that do not provide a view of the threshold with a 1200-foot visual range.

Figure 38 removes all but the visible part of the runway perspective and assumes enough visibility (1800 feet) for illustrative purposes, indicating the paving width and the runway edges. Note the lack of vanishing points, and (though not possible to show in a small illustration) that the scene would appear to the side of the windscreen centerline view (straight-ahead view). 7-A and 7-F would be displaced a greater amount off the centerline of the windscreen than 7-C and 7-D. The illusion derived when the aircraft is heading other than parallel to the runway centerline may become a confusing visual cue. The extent of this visual confusion is not known and needs investigation.

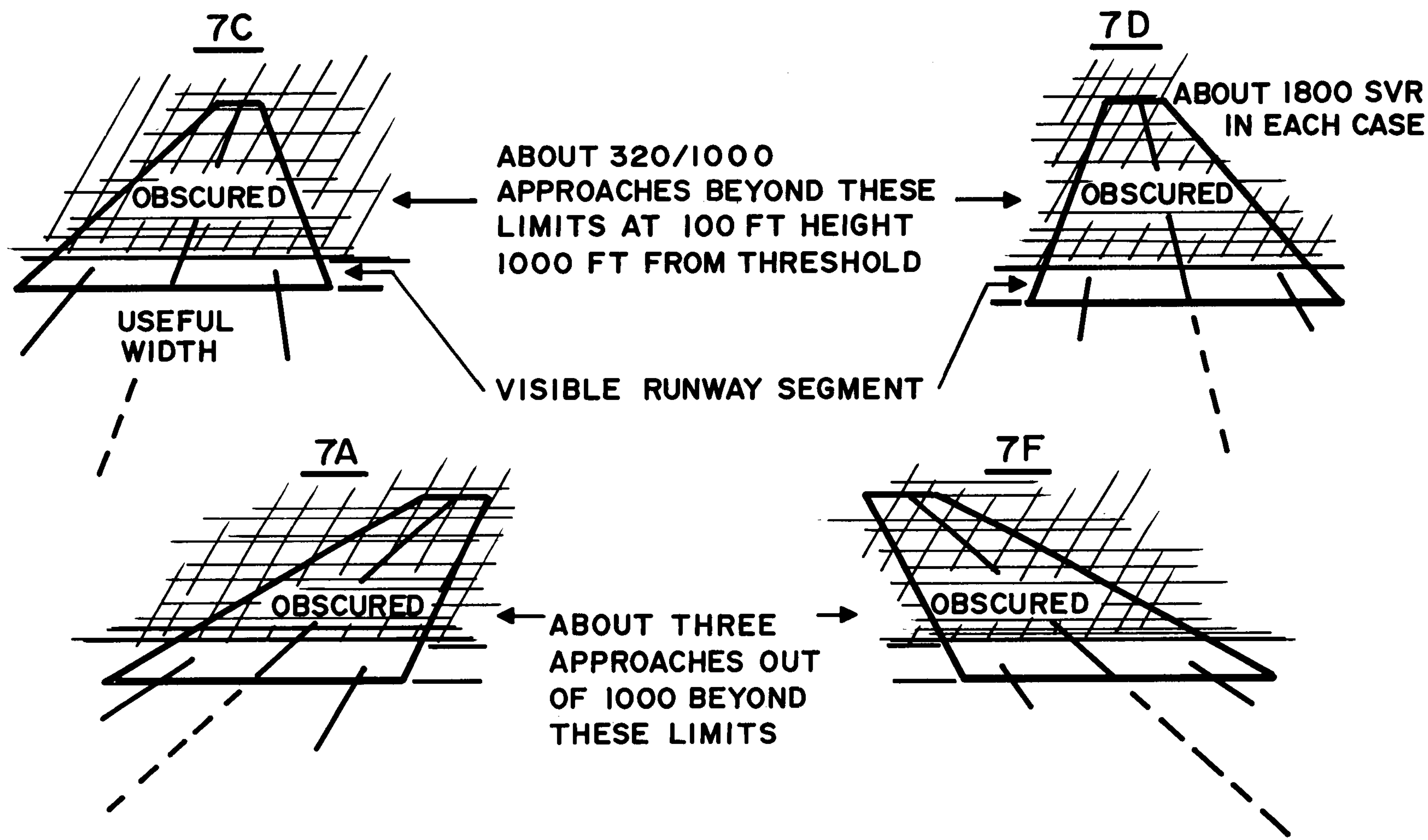


FIGURE 37

RESULT OF LATERAL ERRORS OF 1 AND 3 SIGMA WITH SVR OF ABOUT 1800 FEET AND 1100 FEET FROM THRESHOLD

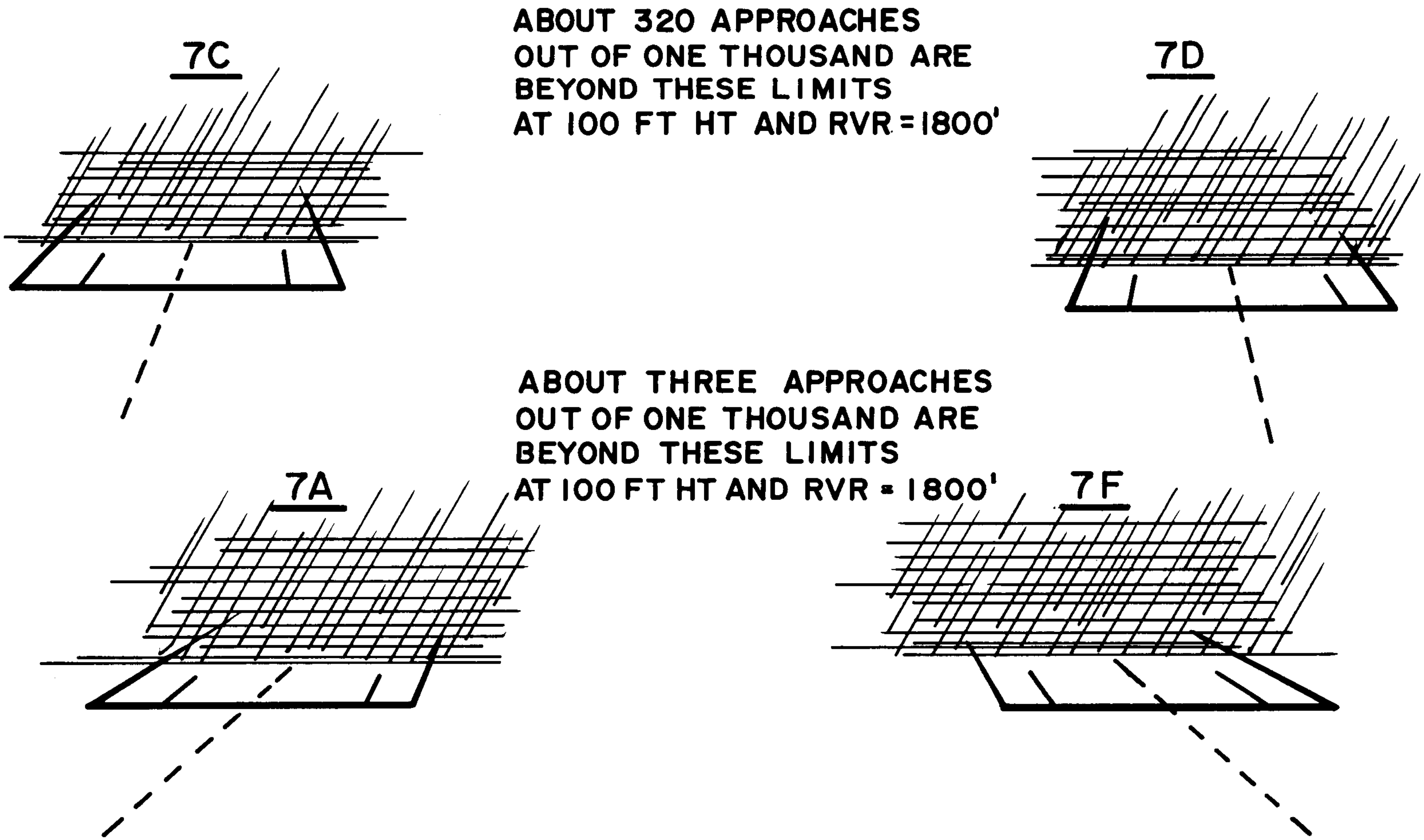


FIGURE 38

THRESHOLD VIEW FROM A HEIGHT OF 100 FEET WITH 1 SIGMA AND 3 SIGMA LATERAL ERRORS AND NO LONGITUDINAL ERRORS

The limited perspectives may cause the pilot to incorrectly judge the placement of the threshold with respect to the straight-ahead view as crab angle. If the perspective were completely present, this would not occur. If he does this, heading and drift due to crab angle may give false guidance illusions.

Figure 39 illustrates the case of the various ILS and flight errors placing the pilot in blocks 1-A and 1-F (see Figure 35 again). Figure 39 attempts to show the enlarged view (relative to the 7-A and 7-F views) now available of the threshold, since the pilot's eyes are now only about 500 feet from threshold. It further shows the 3 sigma error and the perspective of the runway that ensues from these two positions. At these points the threshold is nearly at the cockpit cutoff line, and will soon vanish (in about 1 second) from the pilot's view. What is illustrated is truly a fleeting picture of the threshold as seen from a 100-foot height. The 1200-foot RVR (slant) results in about 700 feet of runway length being visible. Not shown is the fact that any lights or markings diminish in visual prominence with distance, becoming very vague even 300 to 400 feet inside threshold. The clear view of the threshold provides a better judgment of vanishing points and the amount of lateral error. In this case (of seeing the threshold for 1 second) the judgment would undoubtedly be to not attempt a landing, since the side-step to runway centerline is about 110 feet on a 3 sigma basis and 80 feet to a point ±30 feet from centerline (thought to be by some the outside limits of lateral, main gear, touchdown dispersions).

The reduced distance for viewing the threshold in Figure 39 now places the runway centerline about 14 degrees off the center of the windscreen, an amount nearly equal to the vertical (negative) cutoff angle. Depending upon the dimensions of the windscreen of the specific aircraft, part of the structure of the aircraft may now start to obscure part of the view of the runway. However, it is obvious that the threshold subtends a very large viewing angle so that this loss is probably of little

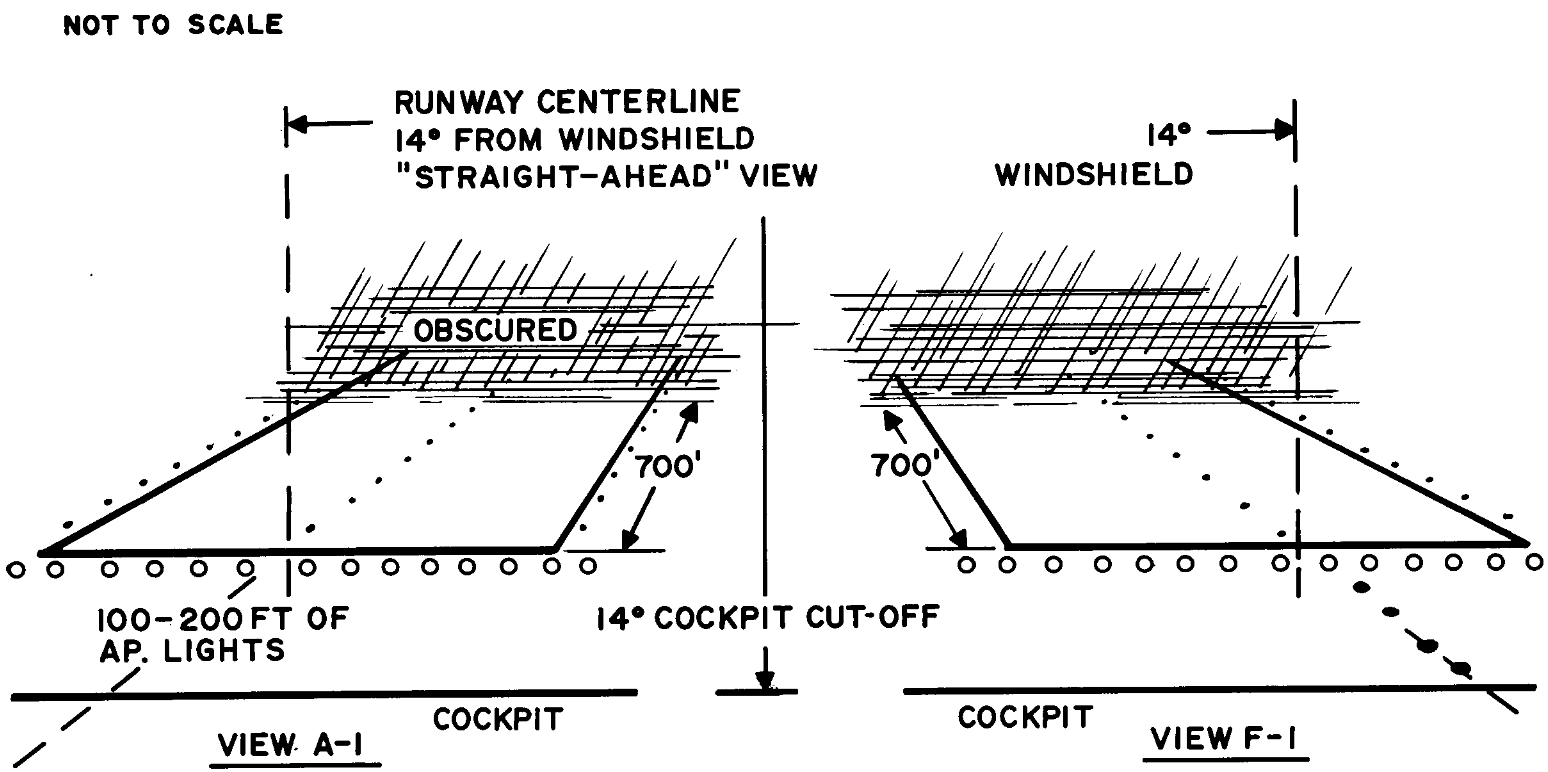


FIGURE 39

VIEW OF RUNWAY FROM 100 FEET/1200 (SLANT) RVR ASSUMING 3 SIGMA ERRORS OF LATERAL AND LONGITUDINAL GUIDANCE AND FLIGHT PERFORMANCE (ABOUT 120-FOOT SIDE-STEP TO CENTERLINE OR A 90-FOOT SIDE-STEP MANEUVER TO 30 FEET OF IT) consequence. It is very evident that the runway is far to the side of the aircraft; however, judgment of height and pitch may be impaired with such a short segment.

This is a good example of the type of test data that is needed. The pilot may not, but obviously should, feel from this view that he is excessively high over the threshold and excessively displaced from centerline. Although the 3 sigma value is three cases per thousand, caution is urged in its use. First, three per thousand is much too large a number of attempts to land from this position, and second, the lack of adequate maneuvering data for various aircraft (when available) may suggest that the safest thing to do is to overshoot. Perhaps this would apply also to the 2 sigma case. The significance of piloting accuracy and immediate decisions for determining the limits of safety under these conditions obviously needs much more research to establish safe limits.

This is to say that the pilot's views of runways, as shown in Figure 39 at 100 feet of height, are probably unsafe conditions for the continuation of a landing of a large aircraft. Whether they are safe for a small, slow aircraft can only be determined by detailed testing and simulation. The question of what is a "safe view" of the runway at the 100-foot height remains unanswered and will probably differ for each aircraft and runway. It will also require enormous and sophisticated visual training of instrument-rated pilots to be able to teach them how to make complex decisions quickly from various limited visual segments. What specific cues he does look for to make the evaluations (which are obviously required) are probably subconsciously or intuitively derived rather than purposely or consciously. The time to make the judgment is very short, and even if much more time were available, what should the pilot look for? Is it the motion of the threshold toward him and its rapidly expanding, subtended angle? Is it the intensity of the lights that increase with decreased visual range to each light? Do the geometrics of the perspective (angles made by the edge of the runway with the threshold) create important, instantaneous impressions on the pilot? Is the displacement of the runway to the far side of the windscreen center important, and is it confused with crab angle?

If "heads-up" displays are considered, how do they work in this situation where they could be in error by relatively large amounts (image size, lateral displacement, aiming point, longitudinal displacement)? All this is permissible in the ICAO CAT II and III ILS Standards as now written. Are the combination of visual cues of perspective geometry, displacement from windscreen centerline, and the "dynamic nature" of the short segment scene all necessary? Which are most sensitive or misleading? Do the large but changing negative angles encountered in viewing the short visual segment for CAT II (starting at 140 to 150 feet of height) create false pitch illusions? Can a pilot fly to a given aiming point without seeing it? Can he estimate its location by viewing short surface segments at negative angles well removed from the actual flight path angle?

V. SIGNIFICANCE OF ANALYSIS

The significance of much of this analysis to steep angle approaches comes about since the amount of time available for stabilization on a normal, flat glide path is much longer than that available for a steep path. Furthermore, the ability to pull up quickly, thus halting sink rate, is reduced with steep-angle approaches. Consequently, any errors in this steep segment of the landing maneuver will be carried over into the lower heights, since little time remains to correct them before reaching ICAO points B and C (about 200 and 100 feet, respectively). This is to say that from point B, on a nominal ILS approach path, the pilot should be stabilized on both glide and localizer paths rather well since he has enjoyed a long, steady-state condition for some time before arriving at this point.

With a contiguous steep-angle approach to landing, this long steady-state condition has not prevailed before the arrival of the aircraft at point B. However, the analysis of guidance errors and flight errors on the steep path or its transition before point B remains the same. A more complex situation associated with the guidance errors (or possibly contributing to them because of poor analysis or rapidly changing information) will exist, but the analysis can still be the same.

Perhaps this analysis of a steep-angle low-visibility approach should have added additional flight error in either sink rate, lateral dispersion, vertical dispersion, or possibly excessive longitudinal speed (gained from the energy expended in pull-out from the rapid descent). For this analysis a new point could possibly be established, which would be the initiation of round-out from the steep approach angle and precedes point B, but is closely related to it. Error analysis of this new point in line with the philosophy given should prove interesting.

VI. STATISTICAL TREATMENTS OF VARIOUS FLIGHT AND INSTRUMENT ERRORS

As indicated at the beginning of this report, only the simplest statistical treatment of the data could be made. Insufficient data exists on dispersions to warrant any of the more sophisticated statistical techniques. However, it is noteworthy that a similar effort, which took some years in various countries and participated in by the FAA, industry, and NASA, relates to vertical separation of aircraft. The ICAO Panel on Vertical Separation utilized inputs from several nations and the United States to establish barometric errors--that is, DOC-7672-AN/860 and subsequent reports. In this case, some 15 identified error factors were included (friction, temperature, backlash, readability, flight technique, etc.), and each was treated as either having a normal or abnormal distribution. The total contributing error elements seemed to be accounted for after some concentrated standardization and testing efforts for 2 to 3 years. Values were assigned to each error based on data such as the NASA VGH data. These measurements and data were then used to determine the 3 sigma separation between two aircraft.

Since 1000 feet of height separation is standard, it was used to determine the number of times it might be exceeded by two aircraft in the same airspace, thus creating a collision risk. Of course, the same lateral and longitudinal position would also have to occur (within the dimensions of the two aircraft for a collision). Two aircraft would not collide even if they were at the same altitude, unless they were in the same, small cubicle of airspace at the same time within the same few seconds.

It is interesting to note the similarity between this altitude separation error analysis and the ILS landing analysis. First, it uses 3 sigma figures, assigning 3/1000 as the critical probability (not 1 or 2 sigma). Furthermore, it cannot always be assumed that there is a normal distribution of certain errors. In addition, the identification of 15 contributory causes indicates that a thorough job was done.

As in the landing example discussed, the flight technical error has a large effect on the total system error. When using the RSS method, several small errors contribute little to total RSS system error, which is composed of a large single error. Certain factors were considered--for reasons beyond this discussion-- to have no distribution such as diaphragm (of aneroid), hysteresis, static pressure, etc. These factors totaled nearly 60 percent of the total error, and the normally distributed factors contributed the remainder. Thus, some errors were added arithmetically to the summation, and RSS treatment was applied to several others. The main point is that there were proper, and apparently good engineering reasons to do this.

It must be emphasized in the ILS guidance example that not all errors contributing to CAT II operations have been accounted for. Only the most evident and previously noted ones (mostly those given in ICAO-FAA standards) are used. For instance, the significance of a "near miss" between two aircraft is quite different from the relationship between an aircraft and ground obstacles when the aircraft is landing under very low visibility conditions. If the analogy of the second aircraft being an obstacle to the first aircraft is made equivalent to the ground, then it is the same as if the second aircraft were always in direct proximity of the ground at a specific height. The runway's "useful paving" area should then be treated more stringently than the collision avoidance of two aircraft. Either some errors must be added arithmetically (as in the worst cases), or different data treatments than normal distributions must be used. Furthermore, the significance of 3/1000 must be considered, since this is but 3 sigma (3 standard deviations). Something approaching a one per million probability may be more appropriate in this terrain collision analogy; this calls for much higher sigma values than are used here. This report is a first effort, and mathematically needs much additional effort when new data warrants it.

The errors that have not been discussed but that should be added in any future CAT II error analysis are:

1. Polarization error.
2. Receiver error associated with signal level; this is serious on long runways since the signal fades seriously because of the height-gain of the ground antennas just prior to touchdown.
3. Perturbations of the courses by parked aircraft.
4. Perturbations of the courses by aircraft taking off or landing in the proximity of the localizer antenna and beams during the approach of a second aircraft.
5. The flight director or autopilot coupler centering errors (DC to AC conversions).
6. The pilot reading errors (parallax, instrument setting accuracy, etc.).
7. Any critical manual reference input such as runway heading (used now in most flight directors, autopilots, etc.).
8. There are several other possible errors such as the offset of the glide path antenna from runway centerline and the related "coning effects" and the tolerances of the monitoring system.
9. Magnetic compass errors contributing to localizer intercept and following errors.

The monitoring system for both the localizer and glide path are more complicated electrically (electronically) than the actual guidance transmitter system. Consequently, since they are the yardsticks (but are not infallible), they must be given some statistical treatment.

With very large aircraft, errors can be introduced if the radiation pattern of the aircraft receiving antenna is not symmetrical but favors one side rather than the other. This introduces errors due to reflections from objects off the runway centerline being favored over the direct guidance signal. Faulty ILS performance was noted because this can shift the localizer course. It is probable that a list of some 15 errors quite similar to those obtained in the barometric altimeter studies could be generated. However, this is beyond the scope of this report since even the five to six errors discussed have in many cases poor statistical histories, so that new ones need careful measurement before being introduced. This should not deter action, since no total-system error figures can be fully applied operationally until this additional step is taken. For one thing, the significance of these other errors is not now known. As confirmation, some of the United Kingdom measurements show greater dispersions than the analysis described in this report. It is possible that these additional errors can play highly significant parts in arriving at a total-system error.

VII. LIMITATIONS OF ANALYSIS

To summarize, only the simplest normal distributions have been used in this report; more sophisticated and more reliable measurements need to be introduced. Perhaps another six to ten error elements can be identified whose magnitudes and statistical treatment are not now known. Finally, even with the limited treatment presented, it is evident that large discrepancies between radio and visual guidance exist that need urgent attention in the flight technical area. This involves flight measurements and ultimately some realistic simulations to determine the true magnitude of these errors. At present, many arbitrary values are used. The "3-sigma" approach to the treatment of these errors may have to be changed to the "one-in-a-million" approach to keep the probabilities commensurate with the very high risk encountered in the operation.

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APPENDIX A

LOW-VISIBILITY LANDING "DECISION-HEIGHT"

Many of the concepts of "decision height" remain unclear. It is generally defined by ICAO and FAA as the height at which a missed approach must be initiated. The Report of the Fourth Air Navigation Conference describes it as follows: "Decision Height:"

> "A specified height at which a missed approach must be initiated if the required visual reference to continue the approach to land has not been established."---"The required visual reference means that section of the visual aids or of the approach area which should have been in view for sufficient time for the pilot to have made an assessment of the aircraft position and rate of change of position, in relation to the desired flight path."

Some obvious questions are the following:

1. How long should the visual surface section or segment be at 200-, 150-, 100-, and 50-foot heights?
2. How long does the pilot observe the required visual reference after it has come above his visual threshold and before he decides or acts?
3. Since "decision height" is now preferred over "critical height," the definition automatically assumes that visual contact has been established before this height is reached. What time elapses and what alternatives exist after decision time?
4. Could a decision height of, say, 150 feet (requiring 5 seconds to recognize that the approach must be abandoned) require that the first visual input to the pilot (1st light or object above visual threshold) occur at around 200 feet? Is this assumed 5 seconds constant for different heights?
5. As the segment of lights visible at lower ceilings becomes shorter, is the pilot's problem and associated time for establishing the required visual reference increased or decreased?
6. What is the time prior to decision time for the pilot to make a reasonable judgment of the aircraft position requiring a lateral correction of 25, 50, 75, 100, or 125 feet? (Is more time needed for judging a greater position error?)

7. Similarly, how long a time is required when, to 6 above, a similar error is added longitudinally such as positions 1-F, 1-A, 10-F, and 10-A of Figure 35?
8. Does it take longer to recognize a cross-track error at one position than another?
9. What effect does heading (other than along or parallel to the runway centerline) have on the pilot's ability to judge these values?
10. Can false illusions be generated with large lateral errors that are coincident with heading errors caused by cross-wind corrections, giving the illusion that the aircraft is heading toward the runway centerline when its track is actually parallel to or divergent from the runway centerline?
11. What is "the desired flight path"? Does the FAA visual landing measurements of 20 feet threshold and about half the glide path reflect the pilot's "desired" path? Or, is it intended that the electronic ILS glide path is the "desired" path?
12. Do the horizontal and vertical directional properties of the lights affect the pilot's judgment when he is positioned as described in 7 above?
13. How does the pilot utilize centerline approach lights to arrive at a "decision" under visual contact conditions associated with a 1200-foot RVR, as illustrated in Figures 37, 38, and 39?
14. How much of a negative, vertical, visual angle can the pilot use?

Many of these questions can be answered by skillful simulation and measured controlled flight tests in low visibility. Figures 15, 16, and 17 indicate that even with 3 sigma and 2 sigma errors an automatically controlled (coupled) aircraft will pass over the edge of the runway rather than over the paving at the threshold.

Even 2 sigma errors (50/1000) can result in one wheel passing over the threshold beyond the paving for large aircraft with wide treads and long bodies (where crab angle can be serious). At least one set of main gear wheels will not be over the concrete when the aircraft passes the threshold. Stating it in different terms: runways 300 to 400 feet wide would be required if a useful width of, say, 90 feet were made available after allowing for errors as now specified (see Figures 12, 13, 15, 16, and 17).

One can argue that the aircraft does not touch down until further down the runway, that the localizer and its errors are converging, and that the errors will eventually bring the aircraft over the paving. The convergence for lateral guidance is far less than the glide path, since the source of the radio signal is about 10,000 feet distant when the aircraft passes over the threshold of a typical major runway. Thus, a wheel of an aircraft, which is following the localizer automatically, will still not be over the paving (for a 3 sigma error) until it is nearly 5000 feet beyond the threshold and about 2000 feet for a 2 sigma error. Of course, with a manual-visual take-over from automatic flight, this would be corrected within the time remaining if, in the pilot's judgment, it is safe to conduct the lateral side-step maneuver and to land afterward. The full automatic-pilot landing analogy is instructive; since human, visual intervention is not assumed, the aircraft would presumably land with one wheel off the runway. Only in case of a failure of the guidance equipment would manual takeover occur in some concepts. Errors are not considered failures if they are within tolerances. Presumably, the pilot in manual control would see the discrepancies noted in Figures 15, 16, and 17 at the threshold, deviate from the procedure, take over and land or abort.

This raises further interesting questions, since the RVR is measured not in the threshold area, but about 2000 feet beyond. What correlation exists between the cockpit view and the RVR figure? The latter is useful primarily for the runway roll-out by visual means. Since the aircraft can be up to 125 feet off centerline near the threshold, and may be on the side opposite to the side where the RVR instruments are installed, the lateral dispersion of visibility might be even greater. Skillfully designed, new concepts of low visibility simulation seem to be in order.

APPENDIX B

LOW VISIBILITY SIMULATION NEEDS

It is evident that new techniques need exploring for creating several low visibility simulation and training devices that will create realistically what the pilot sees--the dynamics of the scene, many typical views of various runway configurations in low RVR, etc. The lights near threshold are colored, have varying intensities, and give important cues to the pilot that should aid him in recognizing fully what light he is viewing. Since the cues are so limited, as shown in Figures 30 through 34, the simulator should recreate the colors, variable intensities, the scatter in low visibility (dazzle effects), and do so with the proper viewing conditions precisely established.

The small blocks of Figure 35 should be created realistically so that the total combination of lateral, longitudinal (and vertical) viewing situations (about 66 blocks) can be utilized in testing human subjects. Each of the blocks should be controllable to a positioning accuracy within its individual dimensions of about 10 feet, since each block is about 40 feet wide and over 100 feet long, as defined in Figures 28 and 35. Positioning and scene accuracies of about 5 feet laterally and 20 feet longitudinally should achieve this result. There will be cases that are considered safe for a landing using a corrective maneuver. Other locations are unsafe. The granularity of the simulation data can be very important.

In each of these positions, the aircraft attitude must also be simulated precisely, since the mixture of heading and displacement cues utilizing short visual segments viewed at large negative vertical angles is quite possible. Furthermore, the rate of change of the cue position is very significant relative to the aircraft axis. The visual cues relative to the estimated ground track of the aircraft, particularly under drift conditions, are likely to be highly significant. Since rather high cross-winds are allowable, unexpected drift rates of up to 10 fps can be encountered. AC 120-20 (FAA) allows 4 knots per 100 feet of height; some higher values have been measured. Thus, the aircraft flight control system may have corrected for an elevated steady-state cross-wind component, which would mean that a crab-angle would exist when the first visual cues come above the pilot's visual threshold.

However, during the time he is attempting to determine lateral error and recognizes his crab-angle, the lateral drift (due to wind shear) can be taking place. Mixed or confusing cues from the limited lights and objects that can be seen are highly vulnerable situations. Thus, the simulation must be able to include not only the various positions for lateral and longitudinal errors for the prescribed heights but also various attitudes and cross-track drift rates to add realism, thus correctly taxing the pilot's ability to judge the situation.

With respect to the distance the pilot sees an object, the first experiment should be to make the lights or ground objects (including colored objects that may differ in various RVR conditions) vanish at controllable RVR conditions. For the first approximation the slant RVR can be assumed to be the same as the RVR (about 15 feet above and parallel to the runway surface). The viewing angles from the cockpit of the short surface segment (2 to 3 seconds for 400 to 600 feet) must be precise. Figures 30 through 34 illustrate that the distance to the most distant object can vary by 14 to 1.

A more sophisticated control of both slant range and horizontal range visibility can be attempted in the design of a later model of a simulator. Extensive research will be needed in low visibility simulation to create a realistic scene for the pilot that is dynamically "believable." The objects must appear with just the right amount of clarity. Sharp objects seem to appear at maximum range with very little contrast--not as "fuzzy" objects as has been assumed by some investigators.

Real time dynamics, side vision, and aircraft flight attitude changes of roll, pitch, sink-rate, etc., must each be realistic, so that the pilot can really become "involved." Since what he sees in the simulator may last for only 6 seconds before touchdown or abort, it is obvious that a great deal of effort must be put forth for what seems like an extremely small testing period. However, if one examines the parameters of lateral, longitudinal, height, speed, heading, roll, etc., and establishes parametric tests that involve runways of differing widths (and useful areas), there can be hundreds of combinations. Today's existing knowledge cannot establish which of these combinations is a safe situation for a maneuver to a landing or whether an abort is indicated.

From this simulation should come a pattern. The 3 sigma errors will probably not be tolerated for an attempted landing from 100 feet or maybe even 150 feet of height. The 2 sigma errors are more likely to be accepted occasionally by a pilot.

Will good simulation teach him cues that permit more rapid, split-second judgments along with more precise and safe judgments? Is it even possible that the 1 sigma errors for CAT II operations will not be very acceptable? This does not really matter, because the objective of the simulation is not to be critical of the ILS guidance system, but to establish what values of realistic errors can be corrected in the few seconds remaining before touchdown in very low visibility. From such a highly realistic, believable testing program will probably come valuable test data taken with airline and military pilots that are now entering the CAT II phase of actual operation. Thus, a critical examination of simulation reality can be made.

Several of the "heads-up" displays could be realistically tested in this manner, since there will be varying amounts of discrepancies in the lateral and longitudinal display of the runway image used by so many of these displays. Even the "runway beacon" systems have several errors in the boresighting, multi-path, lack of full image perspective. How many points make a satisfactory runway outline could be measured. The measure of "confusion" caused by any discrepancies between the basic guidance and instrumentation can be made. The boresighting accuracies between the actual and displayed runway images must be very high. The question is: how high?

APPENDIX C

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